Climatology of Vapour Transport associated with New Zealand Droughts

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Abstract

Drought is a natural hazard which has a wide range of impacts across multiple sectors. While a universal or exact definition of drought is problematic, it is relatively straightforward to classify drought according to the impacted section of the hydrological cycle. Here, hydrological drought is chosen as the focus, as the ecological and socio-economic impacts become more severe as a drought propagates into a hydrological drought. Restraints on hydrological data availability often necessitate the use of standardised indices based on meteorological data, such as the Standardised Precipitation and Evapotranspiration Index (SPEI), as a proxy for hydrological drought. Despite the varied definitions of drought and the complexity in the spatio-temporal development of drought, decreases in precipitation remain a shared characteristic across all drought types, including hydrological drought. Decreases in precipitation are frequently linked to wider atmospheric processes which can act to block the movement of atmospheric moisture, preventing the supply of moisture needed to precipitate out. Thus decreases in precipitation are an outcome of a disruption to the typical pattern of moisture transport over a particular region.

Across New Zealand drought research has remained focused on the spatial and temporal expression of drought. With most precipitation across the country coming from the ocean, a focused study of how this transport of moisture is interrupted during drought events could reveal important information on atmospheric causes of drought occurrence. In the present study, the relationship between drought and atmospheric moisture is investigated across New Zealand and regionally. The 3 month accumulation period of the SPEI (SPEI-3) shows utility in tracking hydrological drought onset, while its ability to capture the impact of snowfall and groundwater processes is questionable across the East Cape, East Coast of South Island and Central Otago regions. An environment to climate approach identifies the relationship between drought and atmospheric moisture featuring declining westerly moisture transport, with a weaker connection to moisture flux indicating the significance of PET to the East Cape, East Coast of South Island and Central Otago regions. A climate to environment approach, using the Self Organising Map (SOM) method, supports the initial findings.

Collectively, the results provide a first look at atmospheric moisture transport over New Zealand during drought events, revealing important information on possible atmospheric mechanisms associated with drought development such as blocking activity or changes in jet stream movement. Further, this thesis highlights the utility of the SOM method for atmospheric research over New Zealand and provides a basis for further detailed investigation, while the analysis of the SPEI-3 has important implications for the New Zealand Drought Index and its possible usage for monitoring hydrological drought.

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List of Abbreviations

AET	Actual Evapotranspiration
AMO	Atlantic Multidecadal Oscillation
CDO	Climate Data Operators
CRU	Climatic Research Unit
CSIC	Consejo Superior de Investigaciones Científícas
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
ERA-40	European Reanalysis Forty
ERA-5	European Reanalysis Five
ERA-Interim	European Reanalysis Interim
IPO	Interdecadal Pacific Oscillation
IVT	Vertically Integrated Water Vapour Transport
MSLP	Mean Sea Level Pressure
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NZ	New Zealand
NZDI	New Zealand Drought Index
PCA	Principal Component Analysis
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PED	Accumulated Potential Evapotranspiration Deficit
PET	Potential Evapotranspiration
RPC	Rotated Principal Component
SAM	Southern Annular Mode
SOI	Southern Oscillation Index
SOM	Self Organising Map
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SSI	Standardised Streamflow Index

SST	Sea Surface Temperature
USA	United States of America
VCSN	Virtual Climate Station Network
WFD	Watch Forcing Dataset
WFDEI	Watch Forcing Data ERA-Interim

1. Introduction

1.1. Background

Drought is an environmental hazard whose impacts are many and varied (Van Loon, 2015). Drought events can result in severe economic costs to agriculture (Kamber *et al.*, 2013), loss of habitat to animal life (Jowett, 1997), and in extreme cases loss of human life (Viste *et al.*, 2013). As a result of the extreme nature of droughts, they have attracted the attention of a wide range of researchers, from economists, social scientists, meteorologists and hydrologists (Mishra and Singh, 2010). One downside to this attention of many different fields has been the competing definitions of drought, due to the need for the researcher to frame the drought event within their field of study. Broadly, drought can be grouped into one of five main categories based on the field within which research is being conducted: meteorological, hydrological, agricultural, groundwater and socio-economic (Mishra and Singh, 2010).

Despite the importance of drought, numerous challenges in drought research do still exist (Kingston *et al.*, 2020; Van Loon, 2015). Drought occurs across different parts of the hydrological cycle and at different spatio-temporal scales (Dai, 2011; Van Loon, 2015). For example, meteorological drought occurs within the atmosphere and across small time scales, while hydrological drought occurs across terrestrial waterways and across long time scales (Van Loon and Van Lanen, 2012; Wilhite and Glantz, 1985). While a hierarchy of drought types has been suggested by numerous authors, from meteorological to agricultural to hydrological (Tallaksen and Stahl, 2014; Van Loon, 2015; Van Loon and Van Lanen, 2012), complex climate-catchment relationships mean that the cascade of drought types from meteorological drought is not a simple linear process. These complex climate-catchment relationships, various spatio-temporal scales and different affected parts of the hydrological cycle all combine to create a challenge when attempting to monitor and identify drought: obtaining representative data (Tallaksen and Stahl, 2014).

To accommodate the challenges associated with data availability, data from one part of the hydrological cycle is often used to represent other parts (Mishra and Singh, 2010). Meteorological data is generally the most commonly available data, and its use within different aggregation periods across time can be used to represent various parts of the hydrological cycle (Van Loon, 2015). Meteorological variables are often used in conjunction with a lag period to account for catchment characteristics when monitoring hydrological drought (Van Loon, 2015), with one example being the Standardised Precipitation and Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010). The SPEI has become widely used since its inception in 2010 by Vicente-Serrano *et al.* (2010) as a means to represent drought, as its multi-scalar characteristics enable it to be used across various time steps. Despite the numerable drought definitions and challenges in representing drought across various parts of the hydrological cycle, all drought types share the common characteristic of precipitation deficits (Wilhite and Glantz, 1985).

Decreases in precipitation are an obvious candidate for drought development, but understanding how these decreases come about requires investigating how normal precipitation levels over a region are disrupted, resulting in drought onset (Mishra and Singh, 2010). Questions arise as to where atmospheric moisture is sourced from before it precipitates out, how it is moved through the atmosphere, and how this normal passage is disrupted (Hannah *et al.*, 2014). One way in which these questions can be answered is by investigating atmospheric moisture fluxes. These fluxes represent the transport of moisture within the atmosphere, from sources of moisture as evaporation from a surface to its sinks as precipitation, both of which occur over land and oceans (Dirmeyer *et al.*, 2009a). While a direct connection does not exist between atmospheric moisture flux and precipitation (Gimeno *et al.*, 2010), the lack of atmospheric moisture flux is frequently seen as a sign of reduced precipitation over a region (Stojanovic *et al.*, 2018). Therefore by investigating the transport of moisture from its sources to sinks, insight is gained as to how the disruption of this transport can lead to decreases in precipitation across a region (Stojanovic *et al.*, 2018).

This transport of atmospheric moisture from evaporative sources across land and oceans to the atmosphere is termed the atmospheric bridge by Hannah *et al.* (2014).

Disruptions to the normal passage of moisture across this bridge has been linked to drought development by Hannah *et al.* (2014) and Stojanovic *et al.* (2018). Blocking of high pressure systems (Şahin *et al.*, 2015) or shifts in wind belts (Mariotti *et al.*, 2002) have both been shown to be mechanisms for drought development as a result of the disruption of moisture fluxes across a region. In particular, the disruption of moisture transport via high pressure systems is often seen as a strong development factor in drought, due to both the moisture disruption and increased temperatures (Stojanovic *et al.*, 2018). Disruptions in the delivery of moisture across seasons have also revealed a susceptibility towards drought during particular seasons (Liu and Stewart, 2003). By investigating moisture sources and sinks together with the atmospheric bridge, disruptions to the typical transport pattern reveal insight into drought onset, cessation and its spatio-temporal characteristics (Şahin *et al.*, 2015).

Across New Zealand (NZ), most precipitation comes directly from ocean evaporation (Dirmeyer *et al.*, 2009a). Therefore to understand droughts in a New Zealand context, one must understand how the typical transport of moisture from ocean evaporation (source) to precipitation over land (sink) is disrupted. However across New Zealand, drought research has remained focused on the regional expression of drought and associated trends under a changing climate (Caloiero, 2017; Kingston and Treadwell, in press; Salinger and Porteous, 2014). Due to the reliance on hydro-electric power, and agriculture as a major export dollar, droughts can have severe effects across New Zealand (Fitzharris, 1992; McKerchar and Henderson, 2003; Salinger and Porteous, 2014). While research targeted towards characterising the atmospheric patterns during drought over New Zealand have revealed important information on drought development (Porteous and Mullan, 2013; Salinger, 1995; Salinger and Porteous, 2014), no investigation has been conducted into how disruptions in the transport of moisture along the atmospheric bridge may be conducive to drought conditions. Important knowledge can therefore be gained from turning the investigation of droughts over New Zealand towards the study of atmospheric moisture during drought events.

1.2. Aims and Objectives

The following thesis aims to investigate the relationship between atmospheric moisture flux and drought over New Zealand. The proposed research will enable further insight into the development of drought conditions across New Zealand, and specifically the development of drought in conjunction with the atmospheric moisture flux over New Zealand. To do this the following research objectives have been established:

1. Use the SPEI to track hydrological drought over New Zealand and within regions of New Zealand
2. Use an environment to climate approach to explore the relationship between SPEI and the atmospheric moisture flux at a national and regional scale
3. Use a climate to environment approach to characterise the atmospheric moisture flux patterns over New Zealand, and the relationship between these patterns and SPEI at a national and regional scale

1.3. Thesis Structure

This thesis is structured as follows. After the current introduction, Chapter 2 will synthesise the background literature and research which will allow the research objectives to be framed within the current state of knowledge. Chapter 3 will then introduce the methodology used in the current study to achieve the objectives stated above. This methodology is to be applied across New Zealand as a whole, while also across nine select regions which are also identified in Chapter 3. Next, Chapter 4 will set out the outcome of the application of this methodology and present findings which address the research objectives. This chapter will involve presenting the results in three sections: the first relating to the SPEI performance in tracking hydrological drought, the second in the relationship between SPEI and the atmospheric moisture flux using an environment to climate approach, and the third involving the characterisation of atmospheric moisture patterns and the relationship to SPEI using a climate to environment approach. Both the second and third sections also include a regional analysis of the relationship between the atmospheric moisture flux and SPEI.

Chapter 5 will then investigate how these results relate to existing research over New Zealand. The chapter will also provide the basis for accomplishing the research objectives, by framing the results within the context which appropriately addresses the research objectives. Finally Chapter 6 will provide concluding remarks, as well as areas of future research which have been identified during the process of achieving the research objectives, and which will further add to the understanding of the research goal.

2. Literature Review

2.1. Introduction

Droughts are recognised as a major environmental hazard by a wide range of researchers (Mishra and Singh, 2010). While confining drought to one single definition is extremely difficult (Mishra and Singh, 2010), the range of definitions all result in a common theme of an impacted water resource. Drought events have been shown by Robine *et al.* (2008) and Verdon-Kidd *et al.* (2017) to cause millions of dollars of damage to the economy of affected countries as well as costing the lives of thousands of people. The impact of drought is the outcome of the reliance on water resources by growing sectors of society (Trenberth *et al.*, 2014).

In addition to the reliance on water resources by society, it is widely thought that this reliance will become increasingly conflicted under climate change scenarios as a result of competing demands for the resource (Trenberth *et al.*, 2014). Reflecting the multi-faceted impacts of droughts, research into drought has covered a broad range of subject areas. Research ranges from definitions of drought (Dracup *et al.*, 1980) and the quantification of economic and social impacts (Easterling and Mendelsohn, 2000), to attempts to predict drought by linking to wider atmospheric conditions (Moss *et al.*, 1994).

The following review will investigate the multi-faceted aspects of drought research, with the goal of investigating the relationship between atmospheric moisture and transport in association with droughts over New Zealand. This goal will be achieved by evaluating and synthesising the existing literature on drought definitions, drought identification, relationships between drought and atmospheric variables, and by reviewing the utility of synoptic climatology techniques in assessing these relationships. Importantly, the role of atmospheric moisture and its transport will be investigated, by evaluating the existing knowledge on the relationship between drought and atmospheric moisture. Further, the lack of knowledge of atmospheric moisture movements over New Zealand will be revealed, highlighting the importance of the thesis aim and objectives to drought research over New Zealand. The goal of this review therefore contributes towards the aim of this thesis (Chapter 1) by introducing the background knowledge which leads to the identification of research gaps. Both global and New Zealand focused literature will be covered.

This chapter is structured as follows. First, the difficulty in reaching consensus on a universal drought definition will be introduced with a look at the many different types of drought and time periods covered (Section 2.2). A number of research studies will also be introduced which illustrate this difficulty, together with showing the range of research topics that drought research covers. Next drought measurement techniques will be covered, including a discussion on the uncertainties present in the various types of measurement technique and the associated impacts (Section 2.3). After the broader overview of drought, the focus will shift to research on wider synoptic conditions associated with drought occurrence (Section 2.4). This section will also investigate the performance of synoptic climatological techniques (Section 2.4.1), as well as cover the exiting research on moisture transport and drought occurrence across the globe (Section 2.4.4). Research gaps will then be identified in regards to moisture transport associated with drought occurrence in New Zealand, alongside uncertainty in the performance of standardised indices as a measurement of hydrological drought (Section 2.5).

2.2. The Definition of Drought

2.2.1 Difficulties in Definition

Before any analysis can be conducted to address the research aim of this thesis (Chapter 1), the exact definition of drought must be addressed so that the research aim and objectives can be framed within the proper context. Without a clear definition of what a drought is, the type of drought that is to be investigated or what the drivers of that drought are, the research which is to be conducted will not be placed within the proper context, and therefore findings could become easily overstated. Drought is unique as an environmental hazard in that it develops gradually, and consequently creates problems of recognition and perception (Salinger, 1995). The gradual nature of drought introduces conflicting ideologies on the nature and definition of drought onset, severity and termination. For example, drought severity depends on the duration, intensity and spatial extent of the drought event (Wilhite and Glantz, 1985). In addition to this, one must also recognise the demands made by humans and vegetation on the water supply (Wilhite and Glantz, 1985). Therefore, defining drought severity will require acknowledgement of all of these impacting factors, but the relative influence of each is often a point of contention for interested parties.

It is widely believed that a common root of the difficulty in reaching consensus on drought onset, duration and intensity is related to the lack of a universal definition of a drought (Lloyd-Hughes, 2014). What constitutes a drought and how drought is defined remains an area of research which is as yet unanswered (Mishra and Singh, 2010). As a result of the multi-faceted nature of drought, it has been suggested that arriving at a uniform definition is not possible (Dracup *et al.*, 1980). Further, drought is considered a multi-scalar phenomenon - the period of arrival of water inputs to its availability as a usable resource varying considerably (Vicente-Serrano *et al.*, 2010).

Emerging from the literature are five basic classifications of droughts (Mishra and Singh, 2010). A brief definition of each follows. In addition, the reader is directed towards Mishra and Singh (2010) and Wilhite and Glantz (1985) for a more in-depth discussion on each of these drought definitions.

1. Meteorological Drought - A period of time with a lack of precipitation over a region
2. Hydrological Drought - A period of time with low surface and subsurface water resources
3. Agricultural Drought - A period of time with declining soil moisture and consequent crop failure
4. Socio-economic Drought - A period of time with a failure of water resource systems to meet water demands

5. Groundwater Drought - A period of time with declining groundwater levels and low groundwater recharge

The range of drought classifications makes the creation of a universal definition of drought difficult. Does sustained below-average precipitation constitute a drought when groundwater is available to alleviate the precipitation deficits? And what if this is occurring in an isolated region, with little to no impact on human health and activity? Despite this difficulty, attempts were made historically to obtain a precise and objective drought definition which could form the basis for the development of more appropriate drought management strategies (Wilhite and Glantz, 1985).

An outcome of the many different economic and social sectors affected by drought has resulted in scores of definitions been advanced to accommodate the desired definition of that sector (Wilhite and Glantz, 1985). These ranges of definitions and competing ideological perspectives perhaps make it more useful to abandon attempts to create a universal definition of drought and instead acknowledge the multi-faceted aspects of drought, as suggested by Lloyd-Hughes (2014). However, in doing so researchers should specifically acknowledge which drought realm they are operating within (hydrological, meteorological, agricultural). Such specification allows the reader to implicitly understand the limitations of the research in relation to the other drought definitions. Dracup *et al.* (1980) suggest defining drought based on what the user is hoping to achieve or investigate. The difficulty in reaching acceptance on drought definition forces the investigator to instead clearly define the bounds of their research while acknowledging the limitations that will result by doing so (Dracup *et al.*, 1980).

Meteorological, hydrological and agricultural droughts are the most commonly assessed drought classifications (Mishra and Singh, 2010). Hydrological drought events differ in their characteristics from meteorological events, as catchments collect and retain precipitation (Laaha *et al.*, 2017). This exerts a modulating effect on the water deficits, suggesting that a single index based on meteorological or hydrological principles will not accurately capture the drought event (Laaha *et al.*, 2017). Hydrological droughts are a complex phenomenon that integrate many river basin characteristics such as land cover, geology and topography (Van Lanen *et al.*, 2016). They also have a strong propagation effect, propagating out from meteorological or agricultural drought (Van Loon, 2015). Minor meteorological droughts may not be visible when viewed through a hydrological lens, while a series of concurrent meteorological droughts may be visible as one long hydrological drought with differing onset and cessation times (Van Lanen *et al.*, 2016). This illustrates the need for knowledge of the hydrological process by water managers i.e. understanding the propagation of a meteorological drought into a hydrological drought (Van Lanen *et al.*, 2016).

2.2.2 Drivers of Drought

Both precipitation and the atmospheric demand for moisture are noted as having an impact on drought. However, the relative contribution of each is not as certain (Kunkel, 1989). The atmospheric demand for moisture is often measured using Potential Evapotranspiration (PET), which is the maximum evapotranspiration that would occur if available moisture were unlimited (Hounam, 1971). This differs from that of Actual Evapotranspiration (AET), which is constrained by the availability of moisture to meet this atmospheric demand (Kay and Davies, 2008). The assumption of PET that there is unlimited moisture supply is particularly questionable when studying drought, with the use of PET in drought calculations leading to additional uncertainty (Dewes *et al.*, 2017). During drought events, air temperature rapidly increases while relative humidity is rapidly reduced. These combine to severely restrict the moisture supply and introduces a bias into the calculation of evapotranspiration when using PET (Spinoni *et al.*, 2017).

The calculation of PET can take many forms (Section 2.3.3), but commonly involve the use of an atmospheric variable as a means to track the evaporative energy (Lu *et al.*, 2005). Weiss *et al.* (2012) note that prolonged high temperatures combined with low precipitation to intensify drought conditions in the Southern United States of America. They noted that initially precipitation and temperature worked in conjunction, with increased temperature compounding initial conditions brought about by the shortfall in moisture (Weiss *et al.*, 2012). Subsequently, the above-average temperatures played a major role in exacerbating the influence of the reduced moisture (Weiss *et al.*, 2012). During drought development, reduced soil moisture results in a move to greater sensible heat in the partitioning of sensible and latent heat, resulting in an increased vapour pressure gradient and greater evaporative demand (Oke, 1987). Further reductions in soil moisture follow, creating a positive feedback cycle in the development of drought (Kunkel, 1989). The inclusion of only one variable (precipitation) may mask this positive feedback mechanism amongst temperature, necessitating its inclusion when investigating drought. This is commonly performed with the use of PET, with evaporative energy represented by temperature. A strong association between temperature and PET may appear to drive increased drought as a result of increased temperatures, but changes in other meteorological variables may affect PET that compensate or exaggerate this temperature increase (Vicente-Serrano *et al.*, 2014). Possible countering effects on the magnitude of PET from wind speed, relative humidity and solar radiation (Vicente-Serrano *et al.*, 2010) mean that the relative role of evapotranspiration in drought is debatable. These additional variables and associated uncertainty in PET calculations are discussed further in Section 2.3.3.

The representation of evaporative energy via temperature is a source of uncertainty. For example, the inclusion of temperature via a PET calculation may artificially exacerbate drought magnitude in water-limited environments, despite the need for its inclusion at energy-limited environments to adequately explain the onset, severity and persistence of drought over different time scales (Manning *et al.*, 2018). This leads to a contradiction in the use of indices: at energy-limited sites, PET is required to adequately explain the physical processes operating and provide a more accurate description of drought characteristics (Manning *et al.*, 2018). On the other hand, in water-limited environments, the use of PET will show increased availability of energy rather than increased drying of soil when measuring drought severity (Manning *et al.*, 2018).

Recognising the uncertainty in the use of PET in drought calculations, Manning *et al.* (2018) opted instead for the measurement of soil moisture as a more capable measure of measuring drought characteristics. Longer integrations of indices were also better at capturing the persistence of drought conditions, as they provided a means to account for the memory of soil moisture drying during the event (Manning *et al.*, 2018). Short integrations were better able to capture drought onset as they were capable of capturing the short intense period of drying that shifted a meteorological drought into a soil drought (Manning *et al.*, 2018). In investigating the relative influence of temperature on drought, Vicente-Serrano *et al.* (2014) found that decreases in streamflow in Southern Europe coincided with decreases in precipitation. The decrease was however not of the same magnitude, suggesting increased evapotranspiration was affecting the magnitude (Vicente-Serrano *et al.*, 2014). An increase in water demand as a result of increased PET from global climate change models was also likely to affect the future occurrence, intensity and magnitude of droughts in the work of Vicente-Serrano *et al.* (2014). Vicente-Serrano *et al.* (2014) concluded their research by finding that drought variability was controlled primarily by precipitation, but that drought severity was exacerbated by the evaporative demand in the atmosphere. Further, they suggested that more extreme hydrological droughts (increased severity) under climate change scenarios were more favoured due to higher evapotranspiration driven by increased temperatures (Vicente-Serrano *et al.*, 2014). They suggested that this temperature driven severity may be particularly harmful in Southern Europe, where plant species have acclimated to precipitation droughts rather than increased temperature and evapotranspiration which introduces a new source of soil moisture stress (Vicente-Serrano *et al.*, 2014).

2.3. Measurement of Drought

2.3.1 Index Approaches

One of the first widely held successful attempts at creating a drought index was the Palmer Drought Severity Index (PDSI) (Palmer, 1965). This index used precipitation, evapotranspiration and soil moisture conditions in an attempt to create an index that measured the severity of a drought together with helping to identify the onset and cessation of said drought event (Palmer, 1965). However, the index was both relatively complex and limited in its ability to compare different locations and months (Alley, 1984). Guttman *et al.* (1992) in particular identified limited spatial comparability with the PDSI, with the

PDSI-defined extreme droughts not being spatially comparable in terms of identifying rare events. They also noted that the frequency of extreme droughts reflected the differences in the variability of precipitation, suggesting precipitation to be the primary driver of drought within the PDSI (Guttman *et al.*, 1992). This same relationship was earlier identified by Guttman (1991), where temperature anomalies had an insignificant effect on the PDSI when compared to precipitation anomalies.

Emerging from research aimed at improving the limitations of the PDSI was the Standardised Precipitation Index (SPI) (McKee *et al.*, 1993). By recognising the importance of precipitation as a main driver of drought and standardising that precipitation, McKee *et al.* (1993) created a simple index which could be compared across seasons and regions. An additional benefit of the SPI was the ability to monitor different drought types depending on the time step chosen i.e. hydrological drought can be estimated using a 12 month accumulation period as a proxy for streamflow data (Bordi *et al.*, 2009). A comparison of both the PDSI and SPI further highlighted the spatial difficulties encountered with the PDSI (Guttman, 1998). The spectral characteristics of the PDSI varied from site to site, while those of the SPI did not when Guttman (1998) analysed comparable time series using spectral analysis. The PDSI also showed a complex structure with a long memory of antecedent conditions, while the SPI revealed a simple moving average process which was more easily interpreted (Guttman, 1998). Despite the findings showing spatial difficulties with the PDSI, it still found use in investigations of changes under climate change scenarios. Dubrovsky *et al.* (2009) noted that the PDSI indicated increased drought risk across the Czech Republic, compared to the SPI which had minimal changes in drought risk when applied over a 12 month time step. The PDSI closely tracked the projected changes in temperature, while the SPI followed projected changes in precipitation, which for the Czech Republic region showed little change (Dubrovsky *et al.*, 2009). The use of evapotranspiration within the PDSI was found to be the determining factor in the differing results, reflecting the increasing significance of temperature changes under climate change scenarios and its impact on drought (Dubrovsky *et al.*, 2009).

Vicente-Serrano *et al.* (2010), recognising the benefits of both the PDSI and SPI, created the SPEI. The SPEI took the water balance approach of the PDSI and combined it with the multiscalar approach of the SPI, enabling comparative studies across regions and months (Vicente-Serrano *et al.*, 2010). The inclusion of evapotranspiration was believed by Vicente-Serrano *et al.* (2010) to make drought analysis more sensitive to climate change, by the inclusion of temperature within the evapotranspiration method. Further research conducted on the performance of the PDSI and SPEI by Vicente-Serrano *et al.* (2015) revealed similar findings to those of Guttman (1991) and Guttman *et al.* (1992). The soil water capacity of the PDSI was found to have a low influence on the index when compared to precipitation and evapotranspiration, with the PDSI shown to be most sensitive to precipitation (Vicente-Serrano *et al.*, 2015). The SPEI showed a high correlation for both precipitation and evapotranspiration, with the high correlation showing equal sensitivity between precipitation and evapotranspiration (Vicente-Serrano *et al.*, 2015). Vicente-Serrano *et al.* (2015) noted that because of the low sensitivity to evapotranspiration in the PDSI, it was particularly poor at tracking changes in drought over semi-arid regions. The strong influence of evapotranspiration in these regions meant that the SPEI was best able to quantify drought, due to the equal sensitivity to precipitation and evapotranspiration (Vicente-Serrano *et al.*, 2015).

The performance of SPI and SPEI was further examined by both Spinoni *et al.* (2017) and Stagge *et al.* (2017). Using the SPEI, increased drying was identified over Southern Europe by Spinoni *et al.* (2017), while Stagge *et al.* (2017) were able to show a divergence between SPI and SPEI across Europe. Similar to the relationship identified by Vicente-Serrano *et al.* (2015), the use of evapotranspiration in the SPEI allows the index to better monitor drought characteristics of semi-arid regions. With Southern Europe being more susceptible to temperature increases as an outcome of the strong temperatures across the region (Vicente-Serrano *et al.*, 2014), the inclusion of PET in the calculation of SPEI results in increased drying (Spinoni *et al.*, 2017). Similar findings were found by Stagge *et al.* (2017), where increases in temperatures (and therefore PET) alongside decreased precipitation were found to enhance drought over Southern Europe. In contrast to Southern Europe, increased precipitation observed over Northern Europe was counteracted by increased temperatures, resulting in little change in drought area (Stagge *et al.*, 2017). In regions showing a decrease in precipitation based drought, Stagge *et al.* (2017) found that the inclusion of PET tended to offset the decrease and shift the trend positive. For regions that showed an increase in precipitation based drought, the inclusion of PET exacerbated the trend (Stagge *et al.*, 2017).

The representation of wet seasons and the measurement of extreme events was noted by Naumann *et al.* (2014) to be the main difference between the performance of the SPI and SPEI indices at representing drought over Africa. Agreement was found between drought onset and recovery, but the representation of the affected area of drought was not in agreement between indices (Naumann *et al.*, 2014). The lack of rain gauges over the area being examined did introduce a high level of uncertainty in the findings of Naumann *et al.* (2014), which suggests that the main source of differences between the drought indicators is the uncertainty in precipitation data sets rather than the estimation of the drought indicators. It was noted by Naumann *et al.* (2014) that standardised indices can become biased when using large numbers of zero or near zero precipitation observations. Because the most common use of drought indices is in dry regions where there is a greater chance of having a large number of zero or near zero precipitation observations, there is a possibility that bias is introduced into the use of standardised indices. The above highlights that no one index is ideal or universally acceptable, and that the choice of indices for drought monitoring should be based on the quality of climatic data and the ability of the index to detect the spatial and temporal variations during a drought event (Morid *et al.*, 2006).

2.3.2 Time Period

As noted earlier, differences in the definition of drought can lead to variations in drought characteristics depending on which lens drought is defined through. To recognise these variations, it is often suggested that an aggregation of indices be used to account for variations in drought definitions (Lloyd-Hughes, 2014). The use of different time scales is a common means by which to account for these variations in drought definitions. In addition, temporal lags between climate signals and drought can be simulated using different time scales in the computation of SPI and SPEI (Vicente-Serrano *et al.*, 2014). When using standardised indices such as the SPI and SPEI, the use of a three month time period was shown by Bordi *et al.* (2009) to be able to characterise meteorological drought conditions across Europe. To represent hydrological drought conditions, Bordi *et al.* (2009) note the use of 12 and 24 month time steps to be appropriate. However the findings of Bordi *et al.* (2009) are not universal, with other studies indicating the usage of smaller accumulation periods (three-six months) to be viable when investigating hydrological drought. As noted by Van Lanen *et al.* (2016), a six month period is considered reasonable at capturing the physical processes of a catchment due to its representation of a typical seasonal drought across Europe. The six month period was noted by Kingston *et al.* (2015) to capture both summer and winter droughts, similarly identified by Van Loon and Van Lanen (2012). Further, the six month period is well correlated with hydrological droughts in both headwaters and lowland basins in the work of López-Moreno *et al.* (2013), with two-four month periods showing a closer correlation across unregulated headwater regions.

Using the SPI, two month accumulation periods showed the greatest responses to river discharge, with longer accumulation periods (eight months) revealing a greater response to reservoir storage (Vicente-Serrano and López-Moreno, 2005). The findings of Vicente-Serrano and López-Moreno (2005) were similarly noted by Lorenzo-Lacruz *et al.* (2010) using the SPEI, with the exception that accumulation periods over 24 months were required across the dominant limestone groundwater regions of the Tagus River. Collectively, when examining drought the choice of time step will closely reflect the accuracy of drought onset, recovery and persistence (Morid *et al.*, 2006). The range of appropriate accumulation periods in existing research highlights that there is some uncertainty in the selection of an accurate time step, with the most appropriate a likely result of catchment characteristics (Van Loon, 2015). The use of standardised indices can be manipulated to perform analysis across drought types without the need for large amounts of additional computation. The time frame chosen for the use of the standardised index should be carefully considered, given the representation of differing drought characteristics that result from the time period chosen.

2.3.3 PET Method Uncertainty

The inclusion of evapotranspiration by Vicente-Serrano *et al.* (2010) in the SPEI allowed for an assessment of the impact of temperature changes via the empirical function of the PET method (calculated using the Penman-Monteith method in later versions). The inclusion of PET improves the indices ability to track drought characteristics but also introduces additional uncertainty. In particular, the choice of evapotranspiration method was noted by Dewes *et al.* (2017) to be a major source of uncertainty in climate change projections using the SPEI. This was similar to the findings of Sheffield *et al.* (2012) using the PDSI.

Method selection to quantify PET has been shown by Kingston *et al.* (2009) and Vörösmarty *et al.* (1998) to result in large differences in the quantity of PET calculated, with Kingston *et al.* (2009) finding differences in the PET climate change signal of over 100% between methods and Vörösmarty *et al.* (1998) showing the sensitivity of hydrological models to PET method selection. The choice of PET method was shown to determine the direction of projections of future water resources by Kingston *et al.* (2009), further highlighting method selection importance and the uncertainty present in projections of freshwater availability as a result. Dewes *et al.* (2017) found that the standardisation procedure performed in the SPEI tended to amplify these divergences between PET methods. They also noted that PET-based drought indicators could overestimate drought predictions under climate change scenarios, as the PET methods did not incorporate plants physiological response to elevated carbon dioxide concentrations (Dewes *et al.*, 2017). A commonly used method is that of the Penman-Monteith method (Kingston *et al.*, 2009; Lu *et al.*, 2005; Vörösmarty *et al.*, 1998), developed by Allen *et al.* (1998) as a method to calculate reference evaporation, defined as the idealised rate of evapotranspiration based on a reference crop at a standard height which is not short of water. Other methods include Hargreaves, Priestley-Taylor and Thornthwaite (Vörösmarty *et al.*, 1998).

Penman-Monteith PET involves the calculation of all four major climatic characteristics determining evapotranspiration: temperature, net radiation, wind speed and relative humidity (Vörösmarty *et al.*, 1998). However, the use of these four variables does place large data requirements on the user, as well as raise important issues around the quality of inputted data when involving more variables (Kingston *et al.*, 2009). It should be noted that the use of more simple methods does still require assumptions to be made on the relationships of other variables, which may not be correct across all regions (Hounam, 1971). For example, simplification of net radiation is possible using the Hargreaves method, recommended in particular for developing countries with incomplete data or issues with data quality (Hargreaves and Samani, 1985). Stagge *et al.* (2017), finding a discontinuity in solar radiation datasets, used the Hargreaves simplification of Penman-Monteith, finding comparable results between both methods.

Kay and Davies (2008) showed that despite the belief that methods involving all variables were the preferred option, temperature-based PET methods often performed similar to, or better than, the more complex formulations. This suggests that in areas where data is limited or of low quality, the use of a temperature-based method may be sufficient. Despite this, such an observation should be treated with caution. Under climate change scenarios the increased dominance of temperature on PET may exert an overwhelming influence when other reducing variables on PET are ignored, introducing bias into the calculation of drought indices. Hobbins *et al.* (2008) in particular warn against the use of oversimplistic methods for calculating PET, with the impact of parametrisation being greater under energy-limited regions than water-limited regions. Their study on the parametrisation of evapotranspiration showed that temperature-based methods were unable to predict the long term trend direction of pan evaporation 46% of the time (Hobbins *et al.*, 2008).

In examining the performance of several PET methods, Vörösmarty *et al.* (1998) found that differences in PET between methods were greatest in climates where evapotranspiration was highest. Such climates are typically hotter and drier, and thus a positive feedback mechanism is generated (Vörösmarty *et al.*, 1998). A hotter and drier climate results in an increase in the dominance of temperature in the calculation of PET via sensible heat fluxes. With increased dominance of temperature comes increased PET, and a hotter and drier climate. Importantly, the drier the climate and larger the PET, the less importance PET estimates become to determining AET (Vörösmarty *et al.*, 1998).

In such situations, AET is restricted by soil moisture and thus the calculation of PET becomes increasingly irrelevant. In drought indices where AET is not calculated and instead PET relied on as an estimate, its use can introduce a significant bias due to the non-recognition of water-limited scenarios. Therefore the selection of a PET method to best represent AET in water-limited regions is of particular importance. The use of PET in drought calculations is also therefore questionable, as such calculations are frequently performed in drier areas where this bias may impact the result.

The choice of PET method will thus be driven by available data and the desire to most accurately model evapotranspiration (Vörösmarty *et al.*, 1998). The choice of PET method should also depend on the prevailing climate of the region to which it is being applied (Hobbins *et al.*, 2008). For assessments using historical and current data, the SPEI remains an ideal candidate for drought quantification as a result of its multiscalar characteristics and comparatively simplistic calculation procedure (Vicente-Serrano *et al.*, 2010). However, its use should be accompanied by an appropriate assessment and acknowledgement of the uncertainty in PET method selection. What is apparent is that when attempting to develop a proxy for hydrological or agricultural drought using time steps alongside indexes solely developed from meteorological parameters, some measure of the atmospheric demand for moisture is required. This is necessary to account for the hydrological processes operating throughout a catchment (Van Lanen *et al.*, 2004). Despite the limitations of PET, its use as a measure of this atmospheric demand does perform well across multiple climates (Lu *et al.*, 2005; Mavromatis, 2007; Vicente-Serrano *et al.*, 2010) and when used in conjunction with standardised indices such as the SPEI does correlate well with hydrological data, as illustrated in Section 2.3.2.

2.4. Synoptic Scale Controls on Drought Occurrence

2.4.1 Synoptic Links

Understanding connections between drought and the wider atmosphere can aid in the interpretation of drought severity and duration. Earlier work in establishing connections between wider atmospheric circulation patterns and drought onset and recovery revealed that the intensity of drought was roughly proportional to the departure from normal at the core of the anticyclone (Namias, 1960). The research by Namias (1960) showed a lag correlation between spring and summer mid-tropospheric height patterns and the onset of drought in the preceding season across the United States of America (USA). Warm dry springtime weather leads to summer drought, while warm summers tended to follow warm dry summers from the preceding year (Namias, 1960). These earlier findings of Namias (1960) signal the potential for prediction of drought conditions by utilising preceding season atmospheric conditions, while simultaneously highlighting the need for anomalous large precipitation events to break significant drought conditions. Despite the earlier findings of Namias (1960), it is clear that connections to wider synoptic circulation systems will vary both spatially and temporally, albeit a common thread will likely exist concerning the presence of anticyclones and the absence of cyclones.

The identification of climatological conditions during drought is an important factor in developing an understanding of how synoptic conditions affect drought onset, severity and termination. For example, Kingston *et al.* (2015) showed that drought events were related to a weakening of the prevailing westerly circulation over Europe. Ionita *et al.* (2017) meanwhile were able to show the 2015 summer drought over Europe was associated with positive 500 hPa geopotential height anomalies over Europe, amongst other variables. Precipitation was also found by Soukup *et al.* (2009) to respond immediately to changes in the 500 hPa geopotential height, providing a means for forecasting using 500 hPa.

The connection of synoptic-scale controls with drought forms part of a wider research realm of connecting streamflow records with wider atmospheric conditions. Drought in this sense is represented by low flow stream records and would be classed as a hydrological drought. Specific research has been conducted on establishing atmospheric circulation patterns associated with both low and high flow events (Ionita *et al.*, 2017; Jacobeit *et al.*, 2006). Connections between atmospheric circulation and drought are frequently identified using concurrent or lagged correlation analysis, using atmospheric indices as a representation of atmospheric circulation patterns (Hannah *et al.*, 2014), with Hannaford *et al.* (2011) identifying continental-scale patterns of drought as related to large scale atmospheric circulation indices. These indexed approaches fall under the classification of climate to environment analysis suggested by Yarnal (1993). These methods are useful in categorising synoptic weather conditions into weather types (Jones *et al.*, 2013; Kidson, 2000). The analysis of weather types and the association with drought allows for an assessment of the broad conditions during the development and termination of drought. For example, Stahl and Demuth (1999) identified that prolonged streamflow drought in Southern Germany was associated with several specific weather types which were classified using a threshold level approach. More importantly, the analysis identified separate regional drought characteristics, with regions being influenced by differing weather types to a greater or lesser extent than others (Stahl and Demuth, 1999). The finding highlights that complex climate-catchment relationships play a significant role in drought development, more so than any specific dominant weather pattern across a region. The findings of regional differences in the time lag of drought response to the relevant weather conditions illustrate the breadth of effects the different weather types can have due to the different spatial and temporal characteristics of affected regions.

It must be noted that the use of these climate to environment approaches does result in the loss of detail in the atmosphere (Hannah *et al.*, 2014), where specific drivers of specific drought events may become lost when solely relying on this approach. To avoid this, Yarnal and Draves (1993) suggest the use of a dual approach, with an environment to climate analysis used alongside climate to environment approaches. Environment to climate approaches are suggested by Yarnal (1993) as a means to capture information lost under the broad climate to environment approaches and which can reveal previously unseen information.

2.4.1.1 Drought Onset and Cessation

Two of the most important drought characteristics are the onset of a drought event and the termination of the event. The definition of drought onset and termination suffers from much the same difficulty as providing a universal drought definition. Parry *et al.* (2016a) proposed defining drought onset and termination as a period of a maximum negative anomaly of precipitation and a return to above-average conditions, while Schwalm *et al.* (2017) suggest termination is triggered when an ecosystem returns to its pre-drought state. However, it also should be acknowledged that drought onset and termination is characterised by its duration, the rate of change and the seasonality (Parry *et al.*, 2016b). As a result of these variations in characteristics, the determination of a uniform definition is difficult, similar to that of a drought definition in general, with onset and termination unlikely to be defined as a single point in time (Parry *et al.*, 2016a).

The criteria for early warnings and false alarms for drought onset and termination vary widely depending on the end-user of such information and their requirements (Steinemann, 2003). In particular, the temporal resolution plays a key role in the determination of drought onset and termination. Both appear to have a range of detection levels depending on the chosen drought indices, with Mishra and Singh (2010) noting the use of specific indices can be regionally specific. For example, Hayes *et al.* (1999) found differing detection levels of drought onset across two commonly used drought indices (SPI and PDSI). Morid *et al.* (2006) found a similar relationship with the seven drought indices used in their study. While the SPI calculated over a three month time step can provide early warning of an oncoming drought, it is also more oscillatory and can generate a greater number of false alarms if the anomalies do not cascade through the hydrological cycle of a catchment (Steinemann, 2003).

Similar to the difficulties in defining a drought, the identification of drought onset and termination will also be determined by the type of drought being investigated. The storage of groundwater within a catchment can act to delay the onset of a streamflow drought due to its offsetting effect, or prolong the cessation of a drought as groundwater reserves are replenished (Parry *et al.*, 2015). These effects would not be captured by a drought index developed solely on meteorological data, potentially leading to substantially different onset and termination dates. In investigating multi-year drought events across Europe, Parry *et al.* (2012) noted that the synoptic conditions leading to the development of drought varied between events. They concluded that each drought episode had a unique signature with the temporal and spatial scales within which it developed (Parry *et al.*, 2012). Despite commonalities in the wider atmospheric conditions and drought characteristics between droughts, establishing a common cause of drought onset was not possible as a result of the unique signatures of each drought event (Parry *et al.*, 2012). It should be reinforced that these were multi-year drought events, with temporally smaller drought events often revealing common characteristics relating to drivers of drought onset and termination (Kingston *et al.*, 2015).

It is also important to select the appropriate threshold for drought onset and termination. A sustained period of drought may be broken into several small, intense droughts when a low drought termination threshold is selected, but the use of a higher termination threshold will create a long multi-year drought out of the same period (Parry *et al.*, 2016b). Drought termination brought about by large precipitation events can also often be overestimated due to the dramatic nature of such events, rather than a gradual return to normal conditions (Parry *et al.*, 2015). The annual precipitation cycle and the probability of receiving excess precipitation are important characteristics of drought termination, and highlight that a serious drought can often take more than one growing season to cease (Karl *et al.*, 1987). Reflecting the varying climatologies across the contiguous USA, Karl *et al.* (1987) identified that a drought had the highest probability of termination during the cold season, driven by the onset of winter precipitation and considerably lower evapotranspiration.

Drought onset was found to be more predictable than its termination by Mo (2011). Over the USA between 1916 and 2007, agricultural drought could take between five to eight months to develop (where the drought threshold level is exceeded) (Mo, 2011). Meanwhile, the termination of an agricultural drought could take anywhere between one and three months (Mo, 2011). With similar hydrological pathways between agricultural and hydrological drought (Van Loon, 2015), and supporting evidence of rapid hydrological drought termination (Parry *et al.*, 2013), similar characteristics can be inferred between agricultural and hydrological droughts. In some cases, drought termination can be bought about by a few strong precipitation episodes, such as the 2012 drought over England and Wales being broken by the wettest April-July period for almost 250 years (Parry *et al.*, 2013). These rapid changes in conditions as a result of a handful of strong precipitation episodes highlights the difficulty in capturing drought onset and termination when only using one temporal period in the drought index (Mo, 2011).

2.4.1.2 New Zealand Synoptic Scale Controls

Similar to the body of international research, drought research across New Zealand has also focused on characterising the general climatic conditions associated with drought development (Salinger and Porteous, 2014), as well as investigations into specific drought events (Porteous and Mullan, 2013). For example, Porteous and Mullan (2013) investigated the 2012-13 drought over the North Island, providing an assessment of its effects and causes as well as an investigation into its severity in a historical context. The immediate cause of the drought was the persistence of slow-moving or blocking high-pressure systems over the Tasman Sea and New Zealand during the summer season (Porteous and Mullan, 2013). Porteous and Mullan (2013) noted that the positioning of the high-pressure system was important for the establishment of drought conditions: a high pressure centred east of New Zealand brought north-easterly airflow anomalies across the country, resulting in widespread drought, with rainfall to the north-eastern North Island preventing the establishment of drought conditions across the north-eastern North Island. This blocking high-pressure system pattern is similar to that noted by Salinger and Porteous (2014) as a drought causing mechanism across the country. A similar blocking high pressure system located in the South Tasman Sea was also identified as a drought causing mechanism by Salinger and Mullan (1999) across the South Island, with both Folland and Salinger (1995) and Salinger (1995) noting a higher occurrence during the winter period. A strengthening of the subtropical anticyclonic belt over northern New Zealand was also seen by Salinger and Mullan (1999) since 1976, which resulted in a change to a more westerly and southwesterly circulation, with an increase in drought risk as a result.

The emergence of specific synoptic weather patterns across regions of New Zealand, together with the regional preference to indexes (Section 2.4.2.1), highlights that drought development is regionally specific (Caloiero, 2018), although persistent anticyclonic activity remains a dominant driver of drought across all regions (Salinger and Porteous, 2014). In further support of the complexity in droughts over New Zealand, Porteous and Mullan (2013) suggested that the dryness of the preceding spring was an important factor in the 2012-2013 North Island drought, highlighting that across New Zealand both spatial and temporal characteristics are important for drought development. The existing research suggests that focused drought research on a regional scale, targeted towards investigating these regional similarities and differences, would likely reveal important information on how individual regions develop drought conditions.

2.4.2 Atmospheric Circulation Indices and Drought Links

Section 2.4.1 highlighted how changes in atmospheric characteristics have been linked to drought onset, duration and termination. These wider synoptic changes are often measured using indexed approaches, which measure an atmospheric variable such as Mean Sea Level Pressure (MSLP), and reduce the variation down to a simple index (Troup, 1965). These indexes frequently oscillate over multiple time scales (Mullan, 1995). As such, they can be used as part of a climate to environment classification suggested by Yarnal (1993).

One major atmospheric index which is frequently linked to drought across numerous regions is the El Niño Southern Oscillation Index (ENSO) (Seager, 2007). Atmospheric variables, such as temperature and precipitation, are in turn linked ENSO phases. However, linkages between the ENSO and drought are often weak, a result of the complexity in the ENSO calculation which cannot be fully characterised by the relative simple statistical techniques used (Pongracz *et al.*, 1999). Nevertheless, changes in the phases of indexes such as ENSO have been linked with both increased and decreased drought development (Kam *et al.*, 2014; Piechota and Dracup, 1996; Vicente-Serrano *et al.*, 2011). The North American drought between 1998 and 2004 was examined by Seager (2007), who established a link with the La Niña phase of the ENSO. Despite this, the termination phase of drought was unpredictable with regards to global ocean conditions (Seager, 2007). In their study of drought risk associated with the Pacific and Atlantic Oceans, Kam *et al.* (2014) found that negative phases of the Pacific Decadal Oscillation (PDO) and the ENSO increased drought risk over the Southern USA, while the Atlantic Multidecadal Oscillation (AMO) appeared to have little influence on drought risk over the USA. Piechota and Dracup (1996) similarly identified increased drought risk in the Pacific Northwest of the USA under El Niño phases, while the Southern USA had increased drought risk under La Niña phases. Collectively, El Niño phases were found to result in more extreme drought events than La Niña events (Piechota and Dracup, 1996).

Describing atmospheric variation solely in terms of an index based on fixed locations does not fully capture the climatic implications of atmospheric circulation, with Kingston *et al.* (2013) noting that this emphasised the value of using an environment to climate approach when trying to understand atmospheric circulation relationships beyond simple linear correlations. Such comments are similar to those of Hannah *et al.* (2014), where the reduction of atmospheric variables down to a simple index results in a loss of detail from the atmospheric processes, leaving weaker teleconnections. While the research into linkages between drought and atmospheric indices remains uncertain, this uncertainty suffers from the same definition issues associated with drought. In investigating the global characteristics of seasonal streamflow and associated variability, Dettinger and Diaz (2000) noted that streamflow records responded more strongly to climate teleconnections than precipitation or temperature. Applying such findings to drought, a hydrological drought would have a stronger connection to climate indices than a meteorological drought. Such a finding further highlights the importance of framing the study of drought in a proper temporal and spatial context. Following comments by Hannah *et al.* (2014), Kingston *et al.* (2013) and Yarnal and Draves (1993), the identification of synoptic links to drought should not be performed solely using climate to environment approaches. Instead, environment to climate approaches can reveal vital information on the relationship, as illustrated by Kingston *et al.* (2013). Therefore any investigation of links between drought and synoptic conditions should take the form of both environment to climate and climate to environment approaches (Yarnal and Draves, 1993).

2.4.2.1 Atmospheric Indices and New Zealand Climate

In a New Zealand context, the establishment of synoptic controls on drought occurrence commonly focuses on the use of atmospheric circulation indexes in an attempt to predict drought occurrence, termination or severity. A common example of this is the Southern Oscillation Index (SOI) and the positive/negative (La Niña/El Niño) phases of its oscillation. Salinger *et al.* (1995) note that annual temperature anomalies in New Zealand were strongly corrected with the SOI. This connection was strongest in northern parts of New Zealand and during the spring, with the weakest connection established during autumn (Folland and Salinger, 1995). Further, Tyson *et al.* (1997) identified that El Niño phases increase westerly winds, producing increased precipitation over the west coast of the South Island, while under La Niña phases, there is a greater incidence of north-easterly airflow over the country and diminished precipitation over the west coast. Broadly, a La Niña phase brings warmer temperatures over most of the country together with decreased rainfall to the south and southwest of the South Island (Sturman and Tapper, 2006). El Niño brings cooler temperatures and decreased rainfall to the east coast of New Zealand (Sturman and Tapper, 2006). Therefore, La Niña phases bring increased drought occurrence to the south and southwest of the South Island, while El Niño brings increased drought occurrence to the east coast of the entire country (Sturman and Tapper, 2006).

Correlations between drought indexes and atmospheric circulation indexes, along with precipitation/temperature and atmospheric circulation indexes have also been investigated across New Zealand (Mojžíšek, 2005). This research supports the international findings of correlations between streamflow and atmospheric indices (Dettinger and Diaz, 2000; Hannah *et al.*, 2014). Correlations established between SPI and New Zealand circulation indices were found to be seasonally robust by Mojžíšek (2005), despite the lack of predictability in the use of the index, similar to comments by Porteous and Mullan (2013). Connections with wider indices over the Southeast region of the South Island showed a strong relationship between the SOI on a seasonal and annual time scale, and with the Interdecadal Pacific Oscillation (IPO) on a decadal scale (Mojžíšek, 2005). However, precipitation variability was governed largely by local circulation influences rather than broad large scale patterns, with the indices representing zonal flow the single most important factor in precipitation variability (Mojžíšek, 2005). Supporting these findings, lake inflows across the Waitaki River were well described by local circulation indices in the work of Kingston *et al.* (2016b). Conversely, possible correlations between temperature/precipitation and the IPO/ENSO were identified by multiple authors (Salinger *et al.*, 1995; Salinger and Mullan, 1999), despite the noted complexity in the relationship by Mullan (1995). The correlation between the SPI and SOI is similar to comments by Dettinger and Diaz (2000), where stronger connections were expected between drought indexes and climate teleconnections. Further illustrating the complexity of indexed approaches, complex relationships between river flow and indexes were identified by McKerchar and Henderson (2003), as too the work of Li and McGregor (2017). The complexity in these relationships should not be understated, as a clear regional signal was present with regards to the strength of the correlation. The weak correlation between precipitation/temperature and climate teleconnections is similarly noted by Dettinger and Diaz (2000) to be expected, following comments by Hannah *et al.* (2014) regarded the loss of atmospheric detail when reducing atmospheric processes to a single index. The loss of this detail explains the lack of connection (or weak/complex correlations) between precipitation/temperature across New Zealand and ENSO or the IPO.

The lack of identified connections between atmospheric moisture and ENSO/IPO supports the use of an environment to climate approach (Kingston *et al.*, 2013), allowing for an understanding of the climate relationship beyond simple linear relationships using indexed approaches. It also highlights comments by Yarnal and Draves (1993) on the utility of adopting both a climate to environment and environment to climate approach, while further suggesting that newer classification methods using a climate to environment approach may reveal vital information that is not visible under an indexing approach (Yarnal, 1993). Despite the apparent connection in some studies (McKerchar and Henderson, 2003; Li and McGregor, 2017), the relationships are complex, with a clear regional preference alongside stronger connections to local scale circulation indices highlighting the complex climate-streamflow relationship across New Zealand (Kingston *et al.*, 2016b; Mojžíšek, 2005). This regional phenomenon is further emphasised in the work of Kingston and Treadwell (in press) and Salinger and Porteous (2014).

2.4.3 Moisture Flux and the Atmospheric Bridge

Atmospheric moisture flux represents the connection between land and ocean and is referred to as the atmospheric bridge by Hannah *et al.* (2014) (Figure 2.1). It also represents an alternative means of investigation into the atmospheric conditions associated with drought development. By investigating the link between the moisture flux associated with ocean and drought conditions on land, insight into the ocean-atmosphere processes which drive river flow variation can be gained (Hannah *et al.*, 2014). For example, the 2002 drought over the Delaware Basin was caused by the Bermuda high pressure shifting over the Southeastern USA from its usual position over the Atlantic Ocean, blocking the passage of marine moisture from cyclonic systems (Kauffman and Vonck, 2011). The connection between ocean and atmosphere moisture fluxes also indicates the potential for predictive abilities based off of oceanic indices or variables such as Sea Surface Temperature (SST). Hoerling *et al.* (2012) identified uniform warming of the tropical oceans as being responsible for widespread drying throughout the Mediterranean. Possible teleconnections were also established with the North Atlantic Oscillation (NAO) during wintertime drying. However as noted by Hannah *et al.* (2014) such connections are not without error, due to the loss of atmospheric detail in the construction of the index.

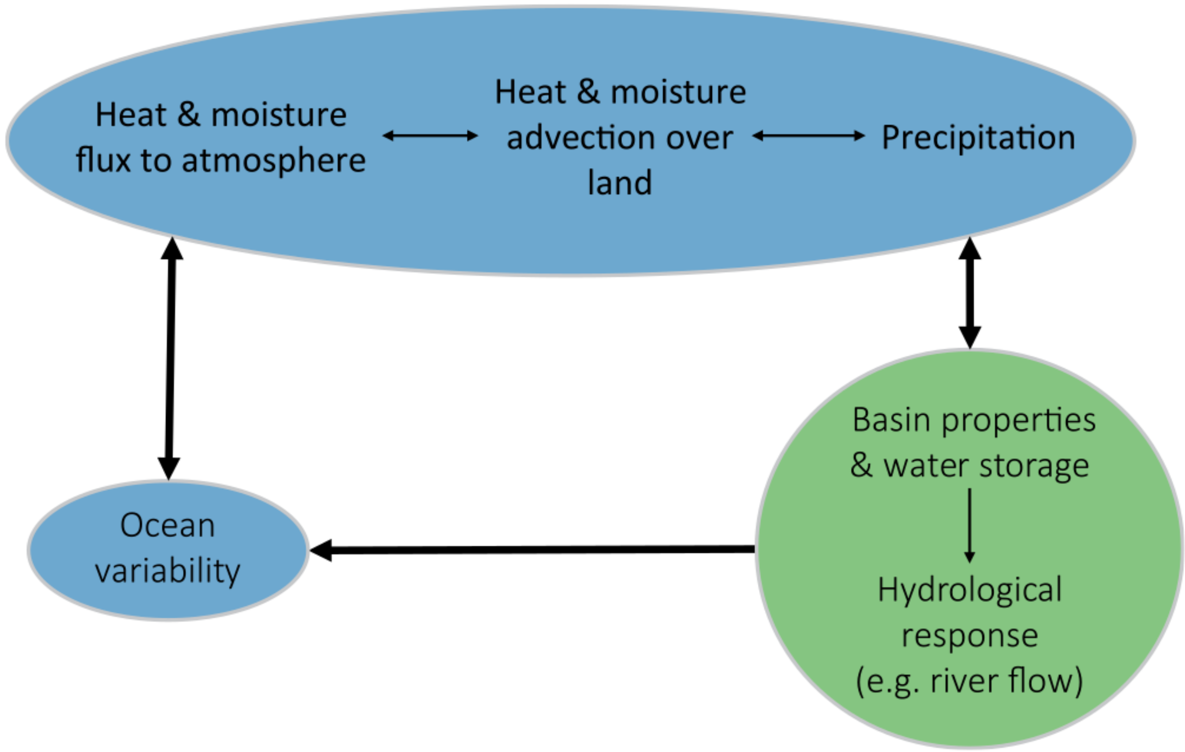

Figure 2.1: Conceptual model of ocean-atmosphere-land-river flow links. Taken from Kingston *et al.* (2020)

Changes in the transport of moisture along the atmospheric bridge can be indicative of drought onset. Swain *et al.* (2016) identified a disruption to the typical moisture transport over California as responsible for widespread drought between 2012-2015, with changes in Northeastern Pacific ridge patterns responsible for the disruption. The delivery of moisture to land via the ocean is not the only mechanisms for moisture transport, with moisture sourced from terrestrial evaporation shown to play a significant part in the sources of moisture for many nations (Dirmeyer *et al.*, 2009a). While over New Zealand moisture is predominately sourced from the ocean, with little recycling of moisture, across many parts of the globe this is not the case (Dirmeyer *et al.*, 2009b). Significant sources of moisture can be attributed to terrestrial sources (Gimeno *et al.*, 2012), as well as from the recycling of moisture and evaporative sources (Dirmeyer *et al.*, 2009a). As noted by Dirmeyer *et al.* (2009a), the dominant moisture source for landlocked nations was that of recycling and evaporation from neighbouring territories, while isolated nations such as New Zealand showed the greatest source of moisture from oceanic sources.

2.4.4 Moisture Transport and Synoptic Conditions

The mechanism for drought occurrence should be viewed in the context of both atmospheric and hydrological processes (Bravar and Kavvas, 1991). Evaporation and precipitation represent the major linkage between atmospheric and oceanic branches of the hydrological cycle (Chen *et al.*, 1994). Globally, water vapour diverges from the high evaporation regions (subtropics) to the high precipitation regions (high latitudes) (Chen *et al.*, 1994). While a significant reduction in precipitation will lead to drought conditions, other atmospheric and hydrological processes, such as changes in temperature or moisture flux, may also contribute to the severity or magnitude of a drought.

The transport of moisture from oceans to continents represents the primary component of the atmospheric branch of the hydrological cycle, forming the link between ocean and continental precipitation (Peixoto and Oort, 1992). The transport of this moisture informs our understanding of the development of extreme events such as floods or drought. A persistent drought over California, which had existed since 2011 until the time of publication by Wei *et al.* (2016) was found to be the result of persistent high-pressure systems off the USA West Coast. Wei *et al.* (2016) also was able to establish a connection to Pacific Ocean SST anomalies but were unable to attribute reduced Pacific ocean evaporation to the Californian drought. They did, however, identify an association between increased Pacific ocean evaporation and floods over California, noting that precipitation was more strongly related to atmospheric circulation off the USA West Coast than ocean evaporation or moisture content in the atmosphere (Wei *et al.*, 2016).

2.4.4.1 Moisture Transport and Drought

The movement of moisture fluxes has also been linked to the wider synoptic conditions to understand the movement of moisture alongside its sources and sinks during drought events. Liu and Stewart (2003) investigated water vapour over the Saskatchewan River Basin. They found that only when a strong Great Plains low-level jet and a dynamic circulation pattern over the basin were present was moisture from the Gulf of Mexico able to move across the basin (Liu and Stewart, 2003). Moisture from the Hudson Bay was only transported across the Saskatchewan River Basin when the Bay was at the north of a deep low-pressure system or to the south of high-pressure system (Liu and Stewart, 2003). Moisture fluxes were also found to vary directions across seasons, with an influx to the north of the basin occurring during fall, winter and spring, before a shift to a southerly influx over the summer period (Liu and Stewart, 2003). These directional changes are in turn linked to the dominant atmospheric pattern which is often prevailing during the seasonal cycle.

Further research into moisture transport during drought conditions has identified that the displacement of prevailing atmospheric centres over the subtropical mid-east Atlantic and north-east Atlantic to the north and south was the general determining factor in wet and dry conditions over the Mediterranean basin (Şahin *et al.*, 2015). Eddy fluxes from the mid-Atlantic propagate over Europe during winter, providing the wet conditions experienced over western and central Europe (Şahin *et al.*, 2015). This contribution of moisture weakens in summer for the Mediterranean basin, resulting in weaker and less frequent frontal activity (Şahin *et al.*, 2015). Subsequently, dry conditions develop and the risk of drought development increases (Şahin *et al.*, 2015).

Following the same method of investigation as Şahin *et al.* (2015), Stojanovic *et al.* (2018) investigated the anomalies of moisture supply during the 2003 drought event over Europe. Over Central Europe, intense moisture reduction was witnessed over the Mediterranean Sea and the Central European region (Stojanovic *et al.*, 2018). Over the Mediterranean region, moisture supply was again reduced over the Mediterranean Sea as well as the Gibraltar region (Stojanovic *et al.*, 2018). The results of Stojanovic *et al.* (2018) indicated drought over the region was the outcome of anomalous subsidence, increased evapotranspiration and reduced precipitation. In investigating the drought and wetness variability in the Tarim river basin in China, Tao *et al.* (2014) found a trend towards increasing SPEI values from 1986. This was linked to increasing humid conditions from 1986, resulting in wetter conditions related to a possible intensification of the global hydrological water cycle (Tao *et al.*, 2014). Composites of water vapour showed moisture transport associated with wet conditions was different to that of dry conditions, with a move towards greater moisture sources from the Arabian Sea and the Bay of Bengal resulting in the shift to decreased drought frequency post-1986 (Tao *et al.*, 2014).

Further examples of the association between atmospheric moisture and drought occurrence are provided by the work of Bai-Zhu *et al.* (2012), Liu *et al.* (2017), Zhang *et al.* (2008) and Zhang *et al.* (2015) in their work over China. Strong changes in moisture flux are present during dramatic shifts from wet to dry periods (Bai-Zhu *et al.*, 2012; Liu *et al.*, 2017), which are in turn linked to increasing geopotential height above the region which displaces moisture movement (Zhang *et al.*, 2008; Zhang *et al.*, 2015). Collectively, the findings indicate strong blocking effects from anticyclonic activity (Zhang *et al.*, 2015) or changes in jet stream movements (Liu and Stewart, 2003) often result in drought development over a region due to declines in atmospheric moisture. Such findings help to develop a wider understanding of how moisture transport is affected during drought events, and reveals vital information on the atmospheric bridge between ocean and land.

2.4.4.2 Moisture Transport and Drought Onset/Termination

The onset and termination of drought has also been linked to the reduction in atmospheric moisture (onset) and the return of that moisture (termination). The influence of tropical cyclones on drought over the Eastern USA was investigated by Kam *et al.* (2013), finding that they acted to shorten the duration and spatial extent of drought propagation. Extreme wet events were shown by Simon Wang *et al.* (2017) to be the outcome of a dramatic switch from atmospheric ridge to trough patterns over California which brought about the cessation of the 2012-2016 California drought. Maxwell *et al.* (2017) investigated what was termed rapid drought cessation over the Southeastern USA, finding that 73% of warm-season droughts were ended by such events.

The wider atmospheric patterns bringing about drought cessation were also investigated by Maxwell *et al.* (2017), showing that frontal storms were the most frequent for drought cessation. Similarly, rapid onset of drought conditions is also possible, with the term flash droughts being proposed as a descriptor by Otkin *et al.* (2018). Here the rate of intensification of drought was the defining variable relating to the terminology, rather than drought duration (i.e. a rapidly developing drought is termed a flash drought as opposed to a short, intense drought) (Otkin *et al.*, 2018). It is important to note that even under increased moisture transport, resulting precipitation is not guaranteed to similarly increase i.e. there is not always a direct relationship between precipitation and moisture transport. This is the outcome of the holding capacity of the atmosphere, with instability or convection still required to generate the required rainfall (Sturman and Tapper, 2006). In particular, the impact of instability is important for the understanding of moisture transport in New Zealand, with the Southern Alps acting as a significant barrier to westerly airflow and creating the necessary disturbance to generate rainfall (Sturman and Tapper, 2006). Forced uplift associated with the topographic extent on the Southern Alps explain around 50% of the variance in rainfall spilling over this alpine divide and thus form a significant factor in the understanding of rainfall on the east coast of New Zealand (Wratt *et al.*, 1996).

Atmospheric rivers are one method by which moisture is transported in the atmosphere (Gimeno *et al.*, 2016). They represent a significant mechanism for moisture transport and as such are frequently studied (Gimeno *et al.*, 2016), with this research commonly being directed towards their impact on flooding due to the extreme precipitation which results from their landfall (Bernhardt, 2014). However, the role of atmospheric rivers and moisture transport on droughts is less well understood. For example, the absence of atmospheric rivers may increase the occurrence of hydrological drought by up to 90% (Paltan *et al.*, 2017). Paltan *et al.* (2017) note that in temperate catchments, the frequency of hydrological droughts increases when atmospheric river driven moisture fluxes are absent. In areas where atmospheric river driven precipitation makes a significant contribution to annual water supply, the absence of such atmospheric rivers would result in intense hydrological droughts (Paltan *et al.*, 2017). Paltan *et al.* (2017) note that the impact of atmospheric rivers on New Zealand is highly likely to be following the pattern of temperate catchments, but remains largely unstudied.

Over New Zealand, atmospheric rivers have been shown to contribute almost 50% of extreme precipitation events (Waliser and Guan, 2017), and up to 80% of runoff in the west and north of the country (Paltan *et al.*, 2017). While atmospheric rivers can be linked to the cessation of drought events (Paltan *et al.*, 2017), changes in the moisture transport outside of atmospheric rivers may be more helpful to the development and maintenance of drought conditions. Specifically, the relationship between moisture fluxes and drought has not been directed investigated. While atmospheric rivers do play an important role in bringing moisture to the country (Kingston *et al.*, 2016a), it is perhaps more valuable to examine the Vertically Integrated Water Vapour Transport (IVT). IVT is one component used in the identification of atmospheric rivers (Dettinger, 2013), so changes in IVT not only provide evidence of possible atmospheric river movements but also reveal key details of the climatology over the region being examined. Examining IVT alongside drought would therefore represent an early investigation across New Zealand of the atmospheric bridge proposed by Hannah *et al.* (2014), revealing important information on the interaction between synoptic systems and the transport of moisture during drought events.

2.5. Summary and Future Research

The preceding chapter has shown that the concept of drought is one which contains many uncertainties. These uncertainties relate to the definition of drought and the uncertainty in the role of atmospheric variables as drivers of drought. The difficulty in clearly defining drought creates a research challenge, as accurate quantification of drought requires a clear understanding of the limitations imposed by selecting a specific drought type. The general synoptic conditions that lead to drought occurrence are well understood. Persistent and blocking systems, changes in jet streams and variation in SST have all been shown to illicit drought responses over land. However, further research is needed in understanding how the connection between circulation types and streamflow responds during drought events. The study of moisture fluxes associated with drought offers an avenue of study which has the potential to complement this wider synoptic analysis work. Across New Zealand, the same global research pattern of drought uncertainty exists. Reflecting the size of New Zealand, the volume of research on atmospheric moisture is limited, yet it is of critical importance, as it offers a measurement of the atmospheric bridge connecting ocean and land surfaces. The overall research question which therefore develops from this is what are the characteristics of vapour transport during droughts in New Zealand, and how does this vary across the topographically complex landscape of New Zealand? This question forms the basis for the research aim of this thesis (Chapter 1).

The cause of much of the uncertainty associated with drought can be traced back to the measurement approach used in drought research: the time period assessed and the variables included or excluded combine to create uncertainty in method selection. One form of drought frequently studied is that of hydrological drought, which has been shown to propagate from meteorological and agricultural drought. The measurement of hydrological drought using streamflow records is difficult as a result of spatially coarse data and the need to isolate out natural flows from anthropogenic influences in the catchment. To accommodate these difficulties, a drought index approach, developed from meteorological variables, can be used on various time steps to mimic hydrological regimes and can act as a proxy for streamflow records. The uncertainty in this approach to measuring hydrological drought results in the identification of research objective number one (Chapter 1): to use the SPEI on a three month time step to track hydrological drought over New Zealand and within regions of New Zealand.

The literature review has also highlighted the uniqueness of drought events, with strong regional variation amongst hydrological drought due to varying climate-catchment relationships. Over New Zealand, similar themes have emerged, with strong regional differences in drought developing as an outcome of the variation in catchments across the country. Investigating the atmospheric bridge between ocean and land can reveal important information on how hydrological drought across these regions, and New Zealand as a whole, responds to changes in atmospheric moisture. Subsequently, research objective number two (Chapter 1) is to explore the relationship between atmospheric moisture and drought over New Zealand and regionally.

The investigation of climatology across New Zealand has also involved many different techniques and methods. Globally the literature suggests both an environment to climate, and climate to environment approach should be adopted to fully characterise the climate-drought relationships. While indexed approaches have revealed limitations due to the loss of detail in their construct, the Self Organising Map (SOM) method provides a relatively new realm to investigate linkages between atmospheric variables and drought. The use of SOMs as a climate to environment approach complements the more common environment to climate approach, by revealing information on the relationship between drought and atmospheric variables which would not be visible when solely using the environment to climate approach. Similar to comments on atmospheric moisture, the usage of SOMs across New Zealand is limited, with only recent studies showing the promising application to atmospheric science across New Zealand. Therefore the third research objective is to further explore the relationship between atmospheric moisture and drought by using a climate to environment approach to characterise the atmospheric moisture patterns across New Zealand. This will be achieved via the use of SOMs as a clustering method of atmospheric moisture.

3. Methods

3.1. Introduction

The previous two chapters provided a background on the uncertainty associated with drought representation. Several objectives were developed to identify the relationship between atmospheric moisture and drought conditions over New Zealand, as well as adding to the understanding of drought characteristics over the country (Chapter 1). The relationship between drought and atmospheric moisture, and the existing knowledge base on linkages between other atmospheric variables and drought development were also introduced (Chapter 2). To achieve the research objectives, drought conditions and atmospheric moisture are quantified from existing databases and the relationship between the two is assessed using several methods (Figure 3.1).

This chapter first describes the methodological approaches employed in this thesis (Section 3.2) and a discussion on the selection of an appropriate drought index to represent drought (Section 3.3). Next, the methods taken to choose the appropriate database for drought conditions (Section 3.4.1), the criteria used to define a drought (Section 3.4.3) and the approach taken to quantify atmospheric moisture over New Zealand (Section 3.4.4) are introduced. This chapter also describes the approaches taken to analyse the relationship between atmospheric moisture and drought. An environment to climate approach is used in conjunction with statistical analysis, which are used to quantify the significance of atmospheric moisture changes (Section 3.5.3). A climate to environment analysis is also performed to complement the environment to climate approach (Section 3.5.4). These methods were then used to reach the research objectives and which form the basis of the results for this thesis.

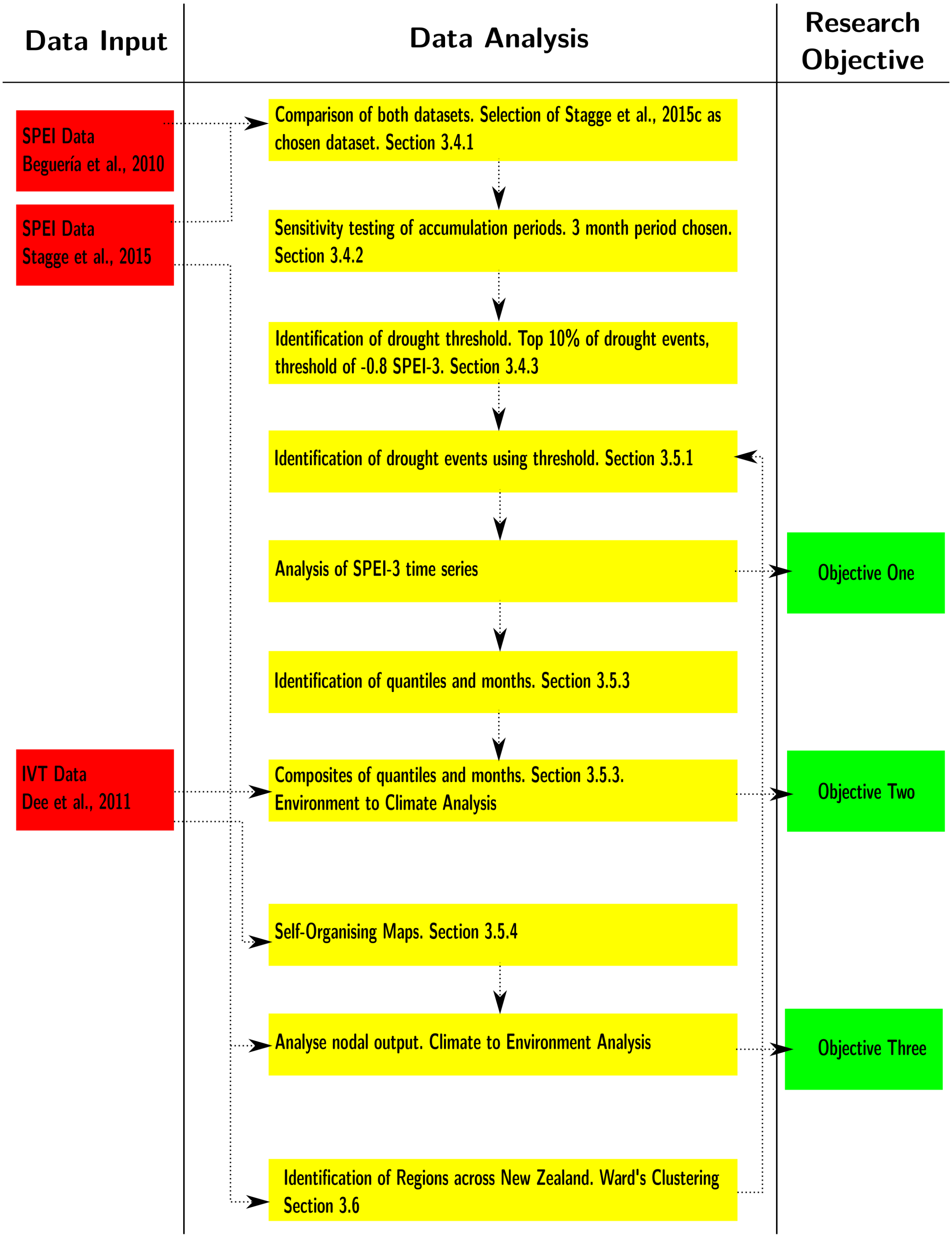

Figure 3.1: Summary flowchart of the methodological process employed in the current study

3.2. Climatic and Environmental Approaches

The study of synoptic climatology aims to investigate the relationship between atmospheric circulation and the surface environment (Yarnal, 1993). This commonly involves analysing atmospheric variables such as MSLP, geopotential height and wind directions (synoptic climatology) in association with drought over a region (the surface environment). This process of identifying links between the synoptic climate and environment falls into one of two approaches: an environment to climate approach, and a climate to environment approach (Yarnal and Draves, 1993). The environment to climate approach involves investigating the atmospheric circulation associated with environmental conditions, while the climate to environment approach categorises the synoptic climate, before examining the environmental conditions during each of these climate categories (Yarnal and Draves, 1993) (Figure 3.2).

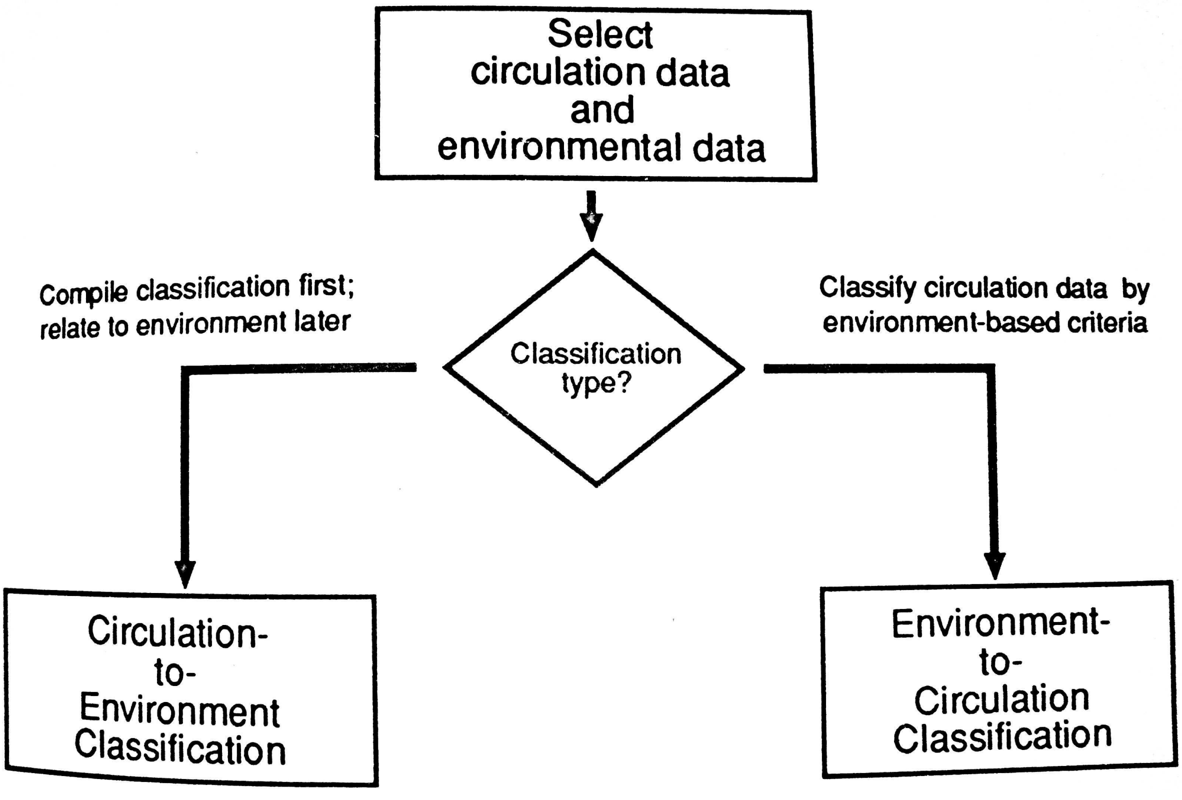

Figure 3.2: Two fundamental approaches to synoptic climate classification. Taken from Yarnal (1993)

Environment to climate approaches help to reveal hidden relationships which are not solely visible using the climate to environment approaches (Kingston *et al.*, 2006; Renard and Thyer, 2019), as there is no a priori choice of synoptic types to prejudice the results (Winkler, 1988). The use of a climate to environment approach helps to identify strong relationships between the synoptic climate and the surface environment, which when performed correctly can help develop an idea of how a particular synoptic regime operates across a region, while also enabling easy analysis of frequency, trends and intensity of the relationship (Yarnal *et al.*, 2001). Therefore the use of the two methods together can enhance the understanding of the relationship between the two variables beyond the use of just one approach (Yarnal, 1993). As a result of this, both approaches are employed in the current study. Composite maps were used to represent an environment to climate approach (Section 3.5.3), while the SOM technique was employed as a climate to environment approach (Section 3.5.4).

3.3. Drought Index Selection

The SPEI (Vicente-Serrano *et al.*, 2010) was selected as the index to be used to analyse the relationship between drought and vapour transport over New Zealand. Because New Zealand has strong regional precipitation patterns (Salinger, 1980a), and regional analysis of drought across New Zealand was an objective of this research, the ability to compare drought in standardised terms between those regions was an important consideration. Such a requirement excluded the use of the PDSI due to its limited functionality in spatial comparability (Guttman *et al.*, 1992). Further, the PDSI is fixed on an annual time step (Guttman *et al.*, 1992), while the SPI and SPEI are capable of being calculated on multiple time steps to estimate varying aspects of drought (Vicente-Serrano *et al.*, 2010). This allows the user to match the temporal resolution of the drought index to the local conditions, and to monitor the desired type of drought.

While the SPI has the option to use different time steps to represent a water balance approach and the standardisation of input precipitation data allows for regional comparisons in relative terms (Bordi *et al.*, 2009), the inclusion of PET in the dataset was identified as an important factor. The use of PET was desirable as it improves the ability of the drought index to track temperature changes across the country and within regions (Vicente-Serrano *et al.*, 2010). However, the representation of evapotranspiration via PET is not without uncertainty, and this uncertainty flows through to the performance of the SPEI in tracking evapotranspiration, as discussed in more detail in Section 2.3.3 and Section 5.3.3.3. Briefly, because actual evapotranspiration is not being measured, in water-limited environments PET is only restricted by the available energy, which can result in an overstatement of evapotranspiration (Manning *et al.*, 2018). This drives lower SPEI values and can result in the identification of drought conditions which may not be physically representative of actual conditions. This limitation is particularly evident in semi-arid regions (Manning *et al.*, 2018).

Notwithstanding the uncertainty in the representation of evapotranspiration via PET, the SPEI was chosen due to its ability to combine the water balance approach of the PDSI with the multiscalar ability of the SPI, its ability to track temperature changes via the use of evapotranspiration, and its ability to enable regional comparisons. The choice of the SPEI over the PDSI and SPI is further supported in research by Spinoni *et al.* (2017) and Stagge *et al.* (2017) which highlights the ability of the SPEI to monitor changes in semi-arid regions. With the regional climate of New Zealand revealing such semi-arid regions (Cossens, 1987) and a previously shown temperature increase across the country (Salinger *et al.*, 2020), the use of evapotranspiration by the SPEI provided a means to monitor the impacts of this temperature increase on drought. Finally, the availability of two pre-existing data sets of SPEI for New Zealand was also a contributing factor in the selection of SPEI over other indices such as the PDSI and SPI.

3.4. Data Selection

3.4.1 SPEI Database

Two databases of SPEI were identified as possible sources of data for use in the analysis of drought across New Zealand. The first data set was prepared by Beguería *et al.* (2010) and was obtained from the Consejo Superior de Investigaciones Científicas (CSIC) (accessed June 12, 2019 via https://spei.csic.es/database.html). It is a global database of SPEI on a 0.5 degrees spatial resolution and covered the period 1 January 1979 until 31 December 2015 on a monthly time step. The reference period for the entire dataset was from January 1901 to December 2005 (Beguería *et al.*, 2010). It was prepared using observed data provided by the Climatic Research Unit (CRU) (Mitchell and Jones, 2005), with evapotranspiration calculated using the Penman-Monteith method (Beguería *et al.*, 2010). The second data set was prepared by and obtained via personal communication with the lead author of Stagge *et al.* (2015). The data set was also a global dataset on a 0.5 degree spatial resolution (Stagge *et al.*, 2015), and covered the period 1 July 1979 to 31 December 2010 on a monthly time step. The reference period for the dataset was the period from January 1970 to December 1999 (Stagge *et al.*, 2015). It was prepared using Watch Forcing Data (WFD) and Watch Forcing Data Era-Interim (WFDEI) (Weedon *et al.*, 2011; Weedon *et al.*, 2014), with evapotranspiration calculated using the Penman-Monteith method with the Hargreaves simplification for solar radiation (Stagge *et al.*, 2015). The WFD and WFDEI datasets are spatially interpolated and bias-corrected versions of the European Reanalysis Forty (ERA-40) and the European Reanalysis Interim (ERA-Interim) reanalysis datasets, respectively (Weedon *et al.*, 2011; Weedon *et al.*, 2014).

The Stagge *et al.* (2015) dataset covered the period 1 July 1979 to 31 December 2010, with the boundaries set over New Zealand at 165°-180°S latitude and -49°-32°E longitude. To aid in comparisons between the two datasets, the Beguería *et al.* (2010) dataset was cropped to the same spatial and temporal extent as that of the Stagge *et al.* (2015) dataset. Climate data operators (CDO) were chosen to crop the temporal and spatial extent of both databases (Schulzweida, 2019). CDO is a command line suite that is primarily used for manipulating and analysing climate data (Schulzweida, 2019), and was used primarily in this study to perform preliminary tasks such as aggregation and cropping of datasets. The reproducible code for this process is shown in Appendix E. For an initial comparison of the datasets, a 3 month accumulation period was chosen (SPEI-3) to represent hydrological conditions (See Section 3.4.2) and give a broad first overview. The monthly mean SPEI-3 was calculated across all grid cells for each month, for both datasets, to analyse the representation of drought across the country (Figure 3.3). Additionally, the mean SPEI-3 value across each grid cell across the entire time period was calculated to identify the average grid cell value across both datasets (Figure 3.4).

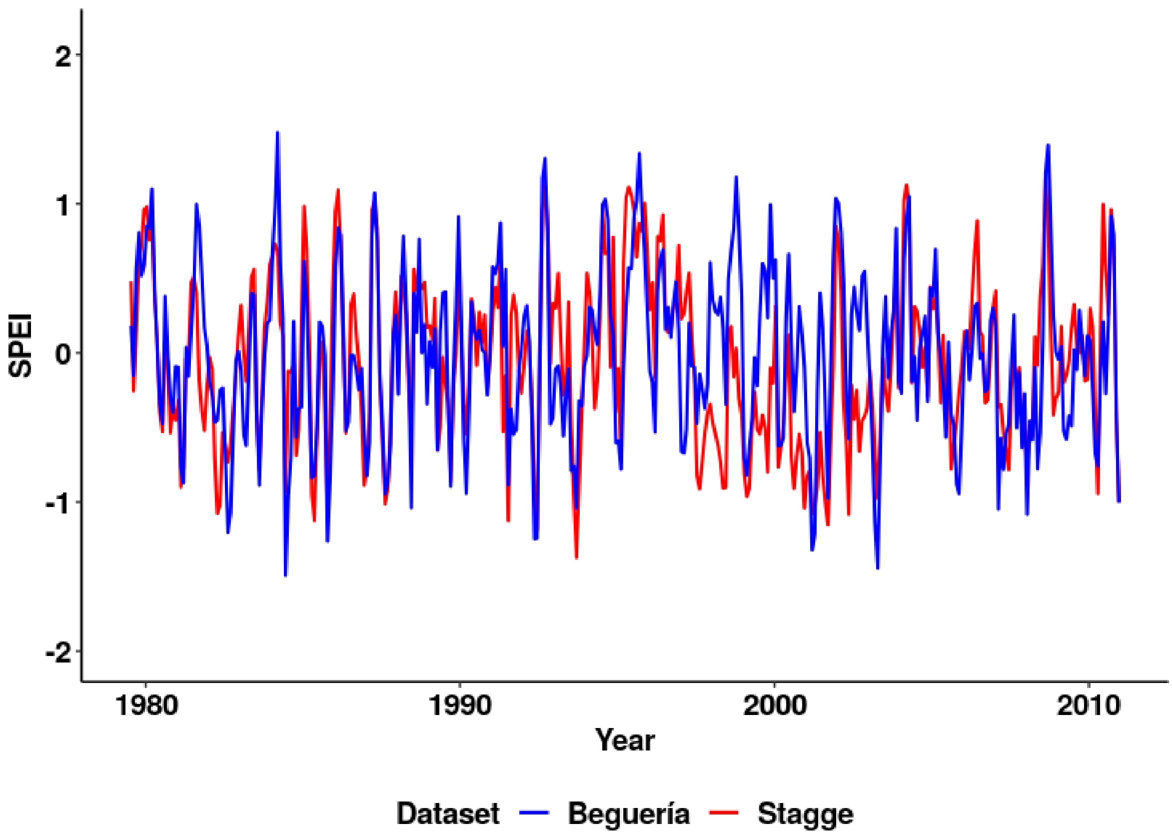

Figure 3.3: Mean 3 month accumulation period SPEI across New Zealand for the period 1 July 1979 to 31 December 2010, using the Beguería *et al.* (2010) dataset and the Stagge *et al.* (2015) dataset

Both the Stagge *et al.* (2015) and Beguería *et al.* (2010) datasets are relatively similar, except for the period from the mid 1990s to the mid 2000s (Figure 3.3). Because this period was a well documented period of increased dryness across the country (Kingston and Treadwell, in press; Mullan *et al.*, 2005) it was assumed that the dataset provided by Stagge *et al.* (2015) better represented the drought conditions across the country. This assumption was tested by examining the data sources of both datasets: the number of stations contributing to the Beguería *et al.* (2010) dataset showed only seven stations used across the South Island of New Zealand. In particular, only four (two each for Dunedin and Christchurch) were located in the eastern South Island, with none in the dry inter-montane regions east of the main divide created by the Southern Alps. This relatively sparse network seemed to be the cause of the difference seen across Central Otago (Figure 3.4), suggesting that the Stagge *et al.* (2015) dataset provides a more realistic and complete record of drought occurrence for New Zealand. As a result, it was chosen as the dataset to be used for further analysis.

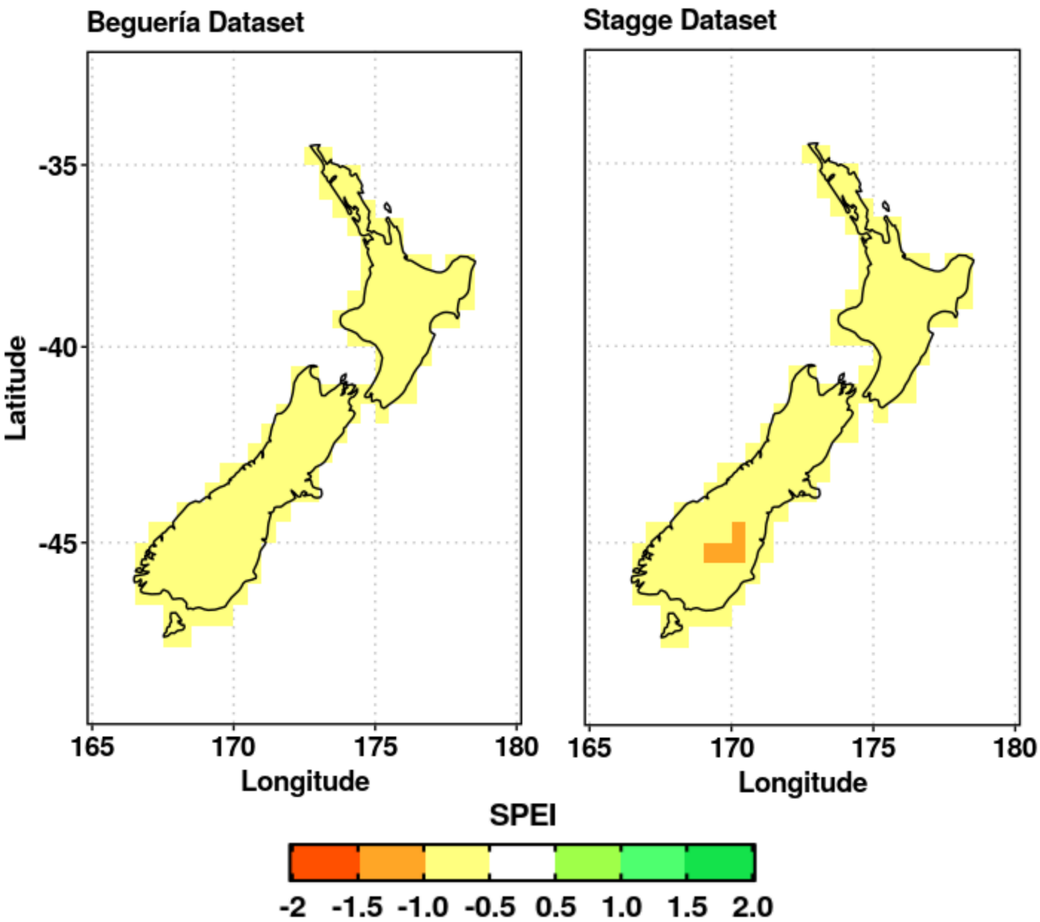

Figure 3.4: Mean SPEI-3 across New Zealand for the period 1 July 1979 to 31 December 2010, using the Beguería *et al.* (2010) dataset and the Stagge *et al.* (2015) dataset

3.4.2 Accumulation Period

An investigation into the performance of the SPEI-3 in monitoring hydrological drought was desired in this thesis, and was to be achieved by replacing streamflow data with the 3 month time step in an attempt to mimic the hydrological processes of catchments across New Zealand (Van Loon, 2015). Because streamflow data is spatially coarse and hydrological records are in a declining trend, it is often easier for the researcher to use more readily available meteorological data (Hannah *et al.*, 2011; Ruhi *et al.*, 2018). It is important to remember that hydrological drought integrates many catchment characteristics such as topology and geology (Van Lanen *et al.*, 2013), which differentiates it from meteorological drought (Van Lanen *et al.*, 2016). Therefore, no temporal resolution of SPEI will ever perfectly represent hydrological drought, as by definition the index does not include this hydrological data, and because individual catchments modify the meteorological forcings in different ways. However, numerous international studies do support the use of different accumulation periods to monitor hydrological drought (López-Moreno *et al.*, 2013; Lorenzo-Lacruz *et al.*, 2010; Vicente-Serrano and López-Moreno, 2005).

The dataset provided by Stagge *et al.* (2015) was available in 1, 3, 6, 12 and 24 month aggregation periods. Analysis of drought conditions was desirable based on the hydrological definition of drought, due to the ecological and socio-economic impacts becoming more severe as drought propagates from meteorological to hydrological (Van Lanen *et al.*, 2016). Accumulation periods of six months or greater are known to reflect hydrological conditions across a wide range of catchment types (Bordi *et al.*, 2009), with the six month accumulation period specifically shown to be well correlated to streamflow in highland and lowland areas (López-Moreno *et al.*, 2013).

In addition to the findings of the applicability of the six month accumulation period by Bordi *et al.* (2009) and López-Moreno *et al.* (2013), research using SPEI has been conducted over New Zealand using six month accumulations periods by Kidd (2015) and Kingston and Treadwell (in press). Despite this, it was felt that a three month accumulation period may be a better representation of hydrological drought over New

Zealand due to the relatively small catchment sizes of the country. The small catchment size means catchments across New Zealand are likely more responsive to meteorological forcings and that shorter accumulation periods may be more representative of hydrological drought. Mol *et al.* (2017), in constructing the New Zealand Drought Index (NZDI), chose a two month accumulation period for SPI, highlighting that a period of two months of well below normal rainfall is sufficient to trigger drought conditions.

The six month accumulation period research conducted by Bordi *et al.* (2009) and López-Moreno *et al.* (2013) was performed over a broad range of hydrological regimes, highlighting its utility across several different catchments. Three month accumulation periods were used by Ionita *et al.* (2017) in their study of the 2015 European drought, with the three month period chosen as it captured the seasonal development of drought and enable comparisons to monthly anomalies. Because this seasonal aspect is important to New Zealand droughts (Waugh *et al.*, 1997), the three month time step was desirable. Further, Kingston *et al.* (2015) note that atmospheric anomalies associated with drought events are very similar whether a three or six month accumulation period is chosen. Finally, because of the previous use of the six month accumulation period by Kidd (2015) and Kingston and Treadwell (in press) to represent hydrological drought, and the use of two month accumulation periods in the NZDI (Mol *et al.*, 2017), it was felt that the use of a three month accumulation period offered an important middle ground from which to test the smaller accumulation periods of the NZDI, particularly as the two month choice was noted as arbitrary by Mol *et al.* (2017).

To test the choice of a three month accumulation period, an analysis was performed on all five accumulation periods. Mean SPEI across each grid cell for the period 1 July 1979 to 31 December 2010 was calculated. Time series of mean SPEI for the entire country on a monthly time step for the period was also calculated, alongside a time series of the percentage of the country in drought (defined in Section 3.4.3).

3.4.3 Drought Threshold

To enable a greater understanding of drought behaviour across New Zealand, individual drought events were required to be identified. To obtain a broad overview of drought conditions over New Zealand, the initial investigation of drought was to be performed on a national level, requiring a national average SPEI-3 threshold to be defined. The national average SPEI-3 threshold value was chosen as a value of -0.8. This value equates to 10% of the time series being below the threshold value (Table 3.1). Within the context of the standardised index descriptors, this falls under the category of mild drought (0 to -0.99) (McKee *et al.*, 1993). In other terms, it is the threshold at which the lowest 10% of SPEI values across New Zealand fall under.

Such a threshold is similar to that defined by Kidd (2015) in their New Zealand study, but remains a higher threshold value than that of previous international studies by Kingston *et al.* (2015) and Tallaksen and Stahl (2014), who instead selected a threshold value equating to the top 20% of events. Similar to the comments noted by Kidd (2015), the 10% threshold was chosen as it offered the balance between providing enough events to enable a robust analysis, while only retaining those events of substantial spatial extent and severity. A higher threshold would include too many events, which may mask the atmospheric conditions associated with the most severe droughts over New Zealand when performing further analysis. A lower threshold would not provide sufficient data to enable a thorough analysis, as only the most extreme events would be included, and thus mask potential drought factors which are not visible except in the most extreme cases.

Table 3.1: Top quantiles of SPEI-3 and the associated SPEI-3 threshold across New Zealand for the period July 1979 to December 2010

Top Quantile	SPEI-3 Threshold
5%	-0.94
10%	-0.80
20%	-0.54

3.4.4 Vertically Integrated Water Vapour Transport

Data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee *et al.*, 2011). The data from ECMWF was in the form of ERA-Interim. While the newly available European Reanalysis Five (ERA-5) dataset was considered for use, ERA-Interim was chosen due to the full availability of data across the study period at the start of this research project. Despite not being the most recent dataset, ERA-Interim remains well tested and has proven reliability in representing atmospheric vapour and transport (Lavers *et al.*, 2012; Rutz and Steenburgh, 2012; Rutz *et al.*, 2014). ERA-Interim does suffer from an issue in the calculation of IVT in the early 1990s (Dee *et al.*, 2011). This limitation was not directly tested, due to the large number of existing research using the ERA-Interim dataset (Mattingly *et al.*, 2016; Rutz *et al.*, 2014; Wei *et al.*, 2016). The issue relates to the calculation of moisture vapour flux, with a change in calculation procedure as a result of new instruments in the mid 1990s. Ideally, several different re-analysis datasets would be utilised in this study, such as those from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (Kalnay *et al.*, 1996), but limitations in the scope of the current research prevented this from occurring.

The parameters downloaded from the ERA-Interim dataset were those of the vertical integral of eastward water vapour flux and the vertical integral of northward water vapour flux, on a 6 hourly time step (accessed July 23, 2019 via https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). The data obtained was for the period 1 July 1979 to 31 December 2010 to match the SPEI-3 dataset time series. The data were accessed across boundaries set over Australasia at 90°-210°E longitude and -70.5°-10.5°S latitude at a resolution of 0.75°. These broad boundaries were set to obtain a general overview of moisture transport across the wider New Zealand region, helping identify jet streams and wind belts.

Using these bounds, the mean IVT field for each calendar month was analysed. All other analysis of IVT was performed after reducing the spatial boundaries to cover only New Zealand. These were set at the same spatial extent as the SPEI-3 dataset, being

165°-180°S latitude and -49°-32°E longitude, but with no land mask being applied, unlike the SPEI-3 dataset. To enable comparisons to the SPEI-3 dataset, the 6 hourly time steps were aggregated into daily and then monthly mean values using CDO operators (Schulzweida, 2019). The reproducible code for processing this data is shown in Appendix E.

Using the vertical integral of eastward water vapour flux and the vertical integral of northward water vapour flux, directional movement of moisture flux can be represented. Calculating the hypotenuse of both fluxes enables the volume of moisture flux to be represented by Equation 3.1, revealing the magnitude of IVT.

$$c = \sqrt{a^2 + b^2} \tag{3.1}$$

where c is total IVT flux (in kg m^1 s^1), a is the eastward IVT flux (in kg m^1 s^1) and b is the northward IVT flux (in kg m^1 s^1)

Monthly mean IVT movements for the period July 1979 to December 2010 were first analysed to gain an understanding of the average annual movement of moisture over the Australasian region.

3.5. New Zealand Drought Analysis

3.5.1 SPEI-3 Events

The first step in the analysis of the relationship between atmospheric moisture and drought conditions was to perform an environment to climate analysis (Yarnal, 1993). Here, the environmental conditions are first defined, before establishing connections to the wider atmosphere during the same periods (Yarnal, 1993). For example, by first defining drought events by SPEI-3 values and grouping SPEI-3 based on monthly occurrence and quantile ranges, and then investigating IVT conditions during the same periods, an environment to climate approach is being employed. Using the drought threshold defined in Section 3.4.3, the monthly SPEI-3 data were filtered to include only those months where the national average SPEI-3 value was below the threshold value (-0.8). Drought events were then identified as those unique months in drought. These national average drought events were then ranked on drought severity, extent and duration. Drought severity was calculated as the total of all SPEI-3 values during the drought month, which includes those grid cells not in drought (i.e. a national average of all SPEI-3 values). Drought extent was calculated as the number of grid cells in drought (below the threshold value) across the country during the drought month. To classify drought duration, consecutive months in drought were grouped, with the month with the highest severity and extent used to represent these multiple month drought events. Having ranked each drought event based on drought severity, extent and duration, a final ranking was able to be generated. This was simply calculated as the sum of the ranked position for each of drought severity, extent and duration, with the tie-breaker being decided by drought severity.

This process resulted in the identification of 22 unique drought events, with composite analysis then performed on the months within each drought event to obtain an average condition associated with each drought event. The use of composite analysis simply involves selecting several maps that satisfy set criteria and averaging them (Yarnal, 1993), and has been shown by Fleig *et al.* (2011) and Porteous and Mullan (2013) to be an effective method to visualise the average conditions associated with the chosen criterion. In this terminology, a map refers to a spatial field of IVT or SPEI-3 (as defined in Section 3.4.1 and Section 3.4.4). Average New Zealand wide drought conditions were represented by taking a composite of all 22 drought events.

3.5.2 IVT

IVT was analysed for each drought event using a four step process. First, using the droughts identified from the SPEI-3 analysis outlined in Section 3.5.1, the IVT fields during the same drought events were also calculated. Because a three month time step was chosen when identifying drought using the SPEI index, the two months prior to drought detection were included in the analysis of IVT, to ensure IVT was shown for the full three month SPEI accumulation period. For example, the drought of August-October 1993 (Table 4.1) is calculated using a composite of the IVT fields for the months of June-October 1993. A composite of the lead up and drought detection months was taken to represent the mean IVT conditions associated with the drought.

Secondly, having represented the conditions during the drought, the mean conditions across the entire time period were also calculated. For example, for the drought of August-October 1993, all June-October months between July 1979 and December 2010 were captured and represented as mean conditions using another IVT field map. Thirdly, anomalous conditions were then able to be calculated, being the difference between the drought event and mean conditions. These anomalies are present for both the moisture flux and direction. For example, the directional anomalies present in Figure 4.5 indicate a decline in westerly flow, or increased easterly flow over the North Island. Because New Zealand is dominated by westerly movement of moisture (Sturman and Tapper, 2006), reference throughout this thesis will largely be towards increases or decreases in the strength of this westerly flow. However, it is important to acknowledge that a declining westerly may instead be indicative of increased easterly flow.

Finally, this anomalous condition was able to be standardised by dividing the anomalous flux by the standard deviation of the flux from each drought event period, across each year, across the entire time period (July 1979 to December 2010). For example, the standard deviation of the August-October 1993 drought is calculated using the June-October period each year between July 1979 until December 2010. Only the IVT magnitude flux can be standardised, therefore the directional movement anomalies were unable to be represented. The IVT fields were analysed for each drought event identified in Section 3.5.1. Composite IVT conditions associated with drought were also analysed, being the mean of IVT across all the above drought periods.

3.5.3 Quantiles and Months

To gain a greater understanding of the relationship between IVT and the SPEI-3 conditions over New Zealand, drought events were grouped based on their quantile rank and month of occurrence. Using these groupings, IVT and SPEI-3 conditions were then analysed for the same periods. This process involves grouping both drought months under SPEI and IVT conditions, and requires specific mention due to the different terminology employed. Because the SPEI-3 is being used to represent drought conditions, reference to a one month drought event is, in reality, a reflection of atmospheric conditions for the preceding two months also. A one month drought event means the SPEI-3 threshold for drought (-0.8) has been exceeded for only one month. However, due to the methodology of the SPEI-3 (Section 3.4.2), the preceding two months are also reflective of developing drought conditions. For example, the drought event of July 1991 (Table 4.1) is a reflection of conditions for May-July 1991, however the drought threshold was only exceeded in July 1991. Because of this, reference throughout this thesis will be made to both SPEI drought months and IVT drought months. SPEI drought months refers to only the month at which the SPEI-3 exceeds -0.8. IVT drought months refers to both the SPEI drought month and the preceding two months. As a result, the number of IVT drought months will be approximately 3 times higher than the number of SPEI drought months.

IVT drought event months were grouped according to the quantile rank of SPEI drought months. Each SPEI drought month was ranked according to the sum of the all SPEI-3 grid cells during the event. This summation includes all grid cells over New Zealand during the drought period, not just those grid cells below the threshold value. The ranking included all 22 drought events and the two month lead up period of each drought event for IVT drought months. This resulted in a total of 37 SPEI drought months and 79 IVT drought months. Quantile ranks were investigated for the 95th, 90th and 80th quantile of SPEI drought months. This resulted in a total of two drought months (95th), four drought months (90th) and eight drought months (80th) under SPEI drought months. The two lead up months to these SPEI-3 quantiles were then also added, to represent the IVT quantile drought months. Under IVT drought months, there were a total of four (95th), eight (90th) and 13 (80th) drought months. A composite of IVT was then taken to analyse the average conditions associated with each quantile. In addition, the mean across the time period July 1979 to December 2010 was also taken for the same drought months in each quantile. The anomalous conditions and the standardised anomaly of IVT magnitude flux were also calculated, following the procedure outlined in Section 3.5.2.

The low number of IVT months associated with each quantile was additionally investigated (Appendix A), by examining the IVT fields for the individual months. All months making up the quantiles showed similar fields to each other as representative of developing drought conditions, except for one month under the 90th quantile (Appendix A) which relates to an additional strong drought event that predominately falls in the 95th quantile. Collectively the results support the notion that the months are representative of the quantiles. Despite this, the uniqueness of individual events cannot be ruled out. For example, the months making up the 95th quantile are from the same event, and attributing characteristics of this event as representative of the top quantile events over New Zealand may be invalid if the event is highly unique.

IVT was also grouped according to the month in which the IVT drought event occurred. This grouping was performed on all 79 drought months (i.e. including the lead up two months), with composites taken of IVT conditions associated with drought during each month. Mean conditions of each month were also calculated across the time period July 1979 to December 2010. Anomalous conditions and the standardised anomaly of the magnitude flux was also calculated, again following the procedure outlined in Section 3.5.2. A composite of SPEI-3 conditions associated with drought during these months was also performed, however as mentioned the number of months this was performed across was 37.

Statistical analysis was performed to test if the groupings of IVT were significantly different from the mean conditions. The Mann-Whitney U test was calculated on each grouping, as the dataset of IVT showed a non-parametric distribution. The process involved testing if the drought composite IVT value in each grid cell was significantly different from that of the mean IVT value at that same grid cell. To limit the influence of the wider region on these tests, the IVT bounds were restricted to the same spatial extent as the SPEI-3 grid cells (Section 3.4.1), with some under-and over-lap as a result of the different grid cell size (0.75 grid cell size for IVT, against 0.5 grid cell size for SPEI-3) (Section 3.4.1; Section 3.4.4).

3.5.4 Self-organising Maps

To aid in the classification of IVT fields over New Zealand, a SOM technique was chosen to categorise monthly IVT conditions. The need to classify IVT fields over New Zealand was necessitated due to the desire to analyse IVT fields from both an environment to climate approach (composite maps, Section 3.5.3), and from a climate to environment approach. SOMs are a classification technique, with their employment in this thesis used as part of the climate to environment analysis approach. These climate to environment approaches first categorise the wider atmospheric conditions in isolation of the environmental conditions on the ground (Yarnal and Draves, 1993). Because the IVT categorisation is taking place exclusive of the SPEI-3 input, and the SPEI-3 is visualised after the categorisation of IVT, the SOM approach fits under similar climate to environment approaches like those of Kalkstein and Corrigan (1986) which employ an eigenvector based synoptic type classification.

A SOM is a type of artificial neural network that is trained using unsupervised learning (Skupin and Agarwal, 2008). The process of unsupervised learning means that the introduced input vectors (IVT fields) do not correspond to known classes (nodes) (Horton *et al.*, 2015). Simply, no prior knowledge of the relationship between the IVT fields and the nodes exists at the beginning of the process (Skupin and Agarwal, 2008). The nodes (classifications) compete for the input vectors (IVT fields) based on the lowest Euclidean distance to the input vector and the weighting of the winning node is adjusted to reduce this distance to the input vector (Horton *et al.*, 2015). Because of this learning process, similar input vectors are driving adjustments of similar nodes, while dissimilarities in the input vectors are becoming accentuated (Skupin and Agarwal, 2008). Therefore the primary role of unsupervised learning and SOMs is in finding clusters in multivariate data (Skupin and Agarwal, 2008).

The SOM procedure involves first initialising the SOM with a user defined selection of a number of nodes (Gibson *et al.*, 2016). Random initialization following the procedure set out in Gibson *et al.* (2016) was employed in the current study, resulting in a first guess map with randomly defined weighting on each node, with each node containing the same dimensions as that of the monthly anomalous IVT patterns (or input vectors). The SOM process then involves introducing a randomly chosen input vector to this first guess map (Skupin and Agarwal, 2008). Using Euclidean distance, each node is compared with the input vector to find the 'winning' node (i.e. the smallest Euclidean distance) (Lee and Feldstein, 2013). As each winning node is found the weighting is updated, together with the neighbouring nodes, to reduce the difference between the node and the input vector (Hewitson and Crane, 2002). This process is repeated for a user defined number of iterations, with each input vector being introduced one at a time (Gibson *et al.*, 2016). The resulting output is a map of nodes where the order relates to the similarity between nodes (Gibson *et al.*, 2016).

SOMs are popular in their use for clustering to produce a low dimensional map (Skupin and Agarwal, 2008). The SOM method is well tested in the climate science realm and has been shown to perform well when compared to other clustering methods (Alexander *et al.*, 2010). Some important differences between SOMs and traditional clustering methods such as Principal Component Analysis (PCA) should be mentioned. Under PCA, non-linearity can be suppressed through the use of linear measures and orthogonality in extracted components (Gibson *et al.*, 2016). SOMs, however, allow for greater use of non-linearity in the data relationship (Reusch *et al.*, 2005). Such non-linearity is beneficial to atmospheric sciences in particular (Chu *et al.*, 2012; Johnson, 2013). A further advantage of SOMs is that the technique preserves the probability density of the input vectors within the node selections (Gibson *et al.*, 2016). This preservation is an important advantage over traditional clustering techniques, as these techniques tend to group less frequent data points in larger classes that are not always representative (Michaelides *et al.*, 2001).

The first step in the creation of a SOM is to select its size and topology (Skupin and Agarwal, 2008). A hexagonal topography was chosen to minimise the distance between similar nodes (Skupin and Agarwal, 2008), with an initial grid size chosen of

5x5. Additionally, the number of iterations was set at 7000, with alpha levels of 99% and 99.5%. These values were all chosen after investigating the node counts and training progress (Figure 3.5).

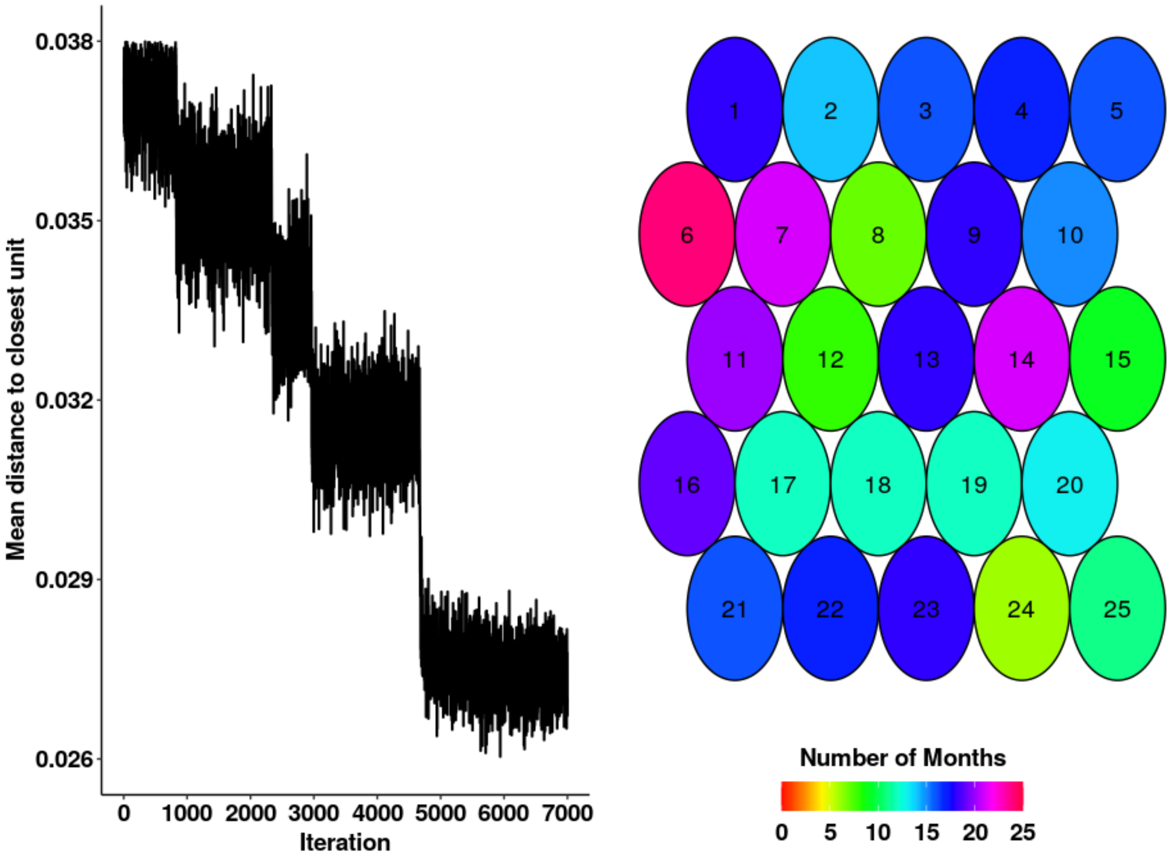

Figure 3.5: Self-organising Map of monthly IVT values for the period July 1979 to December 2010, showing the ideal iterations (left) and node training grid size (right). The order of nodes is noted within the nodal scheme, from one to 25

The number of nodes was chosen after investigating several SOM configurations using the methods of Lee and Feldstein (2013) and Horton *et al.* (2015). For each SOM configuration, the distribution of pattern correlations for every possible node pair was analysed (Gibson *et al.*, 2016), with convergence seen to occur around 25 nodes (Figure 3.6). The root mean square of each node configuration was also seen to stabilise at 25 nodes when using the elbow method (Figure 3.6).

Finally, a 5x5 grid size (25 nodes) provided the most balanced distribution of classification of IVT, with no single node either containing zero observations or containing a disproportionately high number of observations (Figure 3.5).

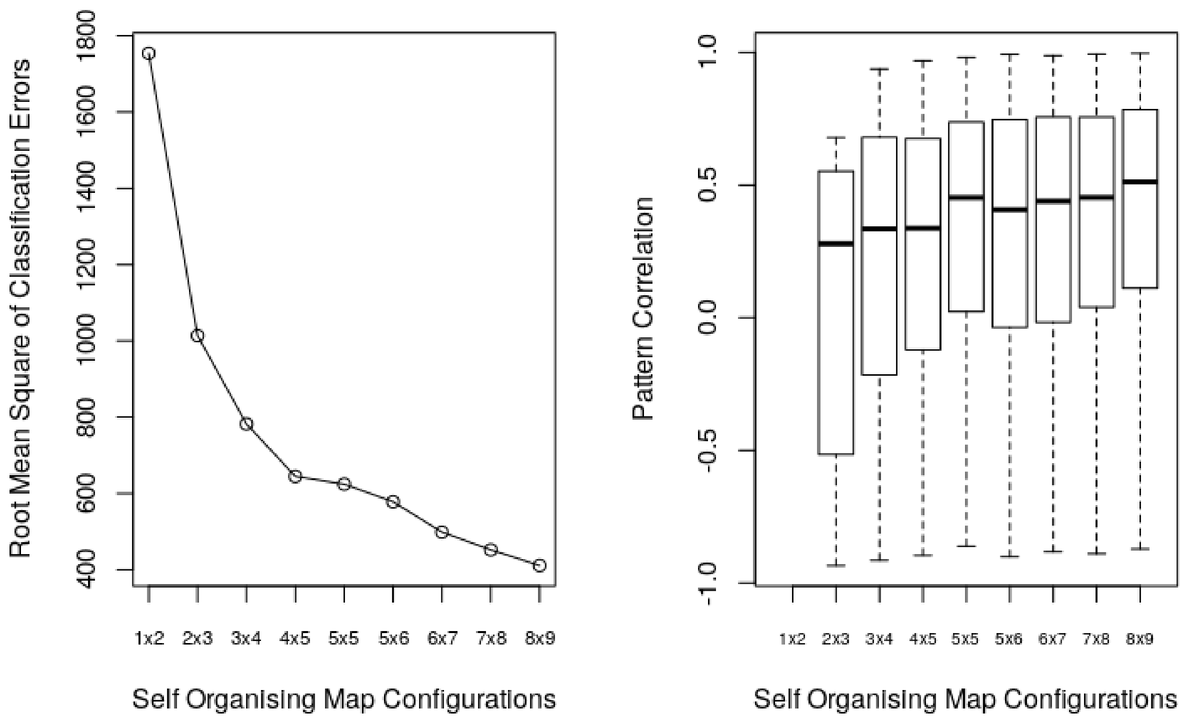

Figure 3.6: Sensitivity testing for various SOM training configurations showing root mean square of classification errors of each configuration (left) and Pearson pattern correlations between each possible SOM node part for each configuration (right)

IVT fields (Section 3.4.4) were then introduced into the SOM algorithm. After performing the SOM analysis on the monthly IVT fields, a single map was created which includes the 25 nodes that classify the average monthly IVT conditions. These are shown in Appendix C.

Having identified the 25 nodes, the anomalous conditions were calculated for each node along the time series from July 1979 to December 2010. Anomalous conditions were defined as the month in question less the mean of all those months in the time series of data, as previously noted in Section 3.5.2. Each IVT anomalous month was then placed into one of the nodes based on the original classification of that IVT month. This process was also repeated for SPEI-3 values, allowing for the analysis of average SPEI-3 conditions during each node. The frequency of each node during SPEI and IVT drought months, as well as during each quantile was performed, enabling identification of specific months were nodes were more common.

3.6. Regional Analysis

To analyse the relationship between IVT and drought across New Zealand on a finer scale, a regional analysis was performed. This process involved performing cluster analysis on the SPEI-3 over New Zealand to identify regions, with the relationship between IVT and SPEI-3 at each region then being examined. A traditional cluster analysis was chosen over the use of the SOM method used earlier. The SPEI-3 data does not contain the same level of spatial dimensionality as IVT fields (IVT contains both directional and magnitude values), meaning that the benefits of the SOM method would not be as widely felt if applied to the SPEI-3 (Hewitson, 2008). Further, the use of cluster analysis is relatively common when grouping drought or hydrological data, as illustrated by Fleig *et al.* (2011), Hannaford *et al.* (2011) and Kingston *et al.* (2011).

Regions were first identified using the hierarchical clustering technique of Ward's clustering, with Euclidean distance. Ward's method was chosen as the hierarchical technique both due to its use by Kingston and Treadwell (in press) using the same dataset as the current study, and due to the method minimising the loss of information at the joining of each cluster (Bijnen, 1973). The process starts by regarding each data object (each grid cell, for each month) as a different cluster, and continues by searching for similar clusters (Kotsakos *et al.*, 2013). This is then joined with the original cluster, and the process repeats until the user defined number of clusters is reached (Kotsakos *et al.*, 2013). The use of Ward's method means that at each join to the original cluster, the loss of information is as small as possible, while also being quantifiable (Bijnen, 1973). The choice of the number of clusters was chosen after examining both the dendrogram of the cluster analysis, alongside the use of the elbow method (Figure 3.7). Nine clusters were identified as the number of clusters which best represented the SPEI-3 conditions across New Zealand after investigating the results from the elbow method, with nine regions also enabling the identification of both islands as well as the separation of Northland and Auckland/Waikato. Kingston and Treadwell (in press) used six clusters in their study of SPEI-6 values. Because the current study used the same methodology and dataset as Kingston and Treadwell (in press), clustering was also performed using six clusters to enable direct comparisons between SPEI-6 and SPEI-3 on a spatial level.

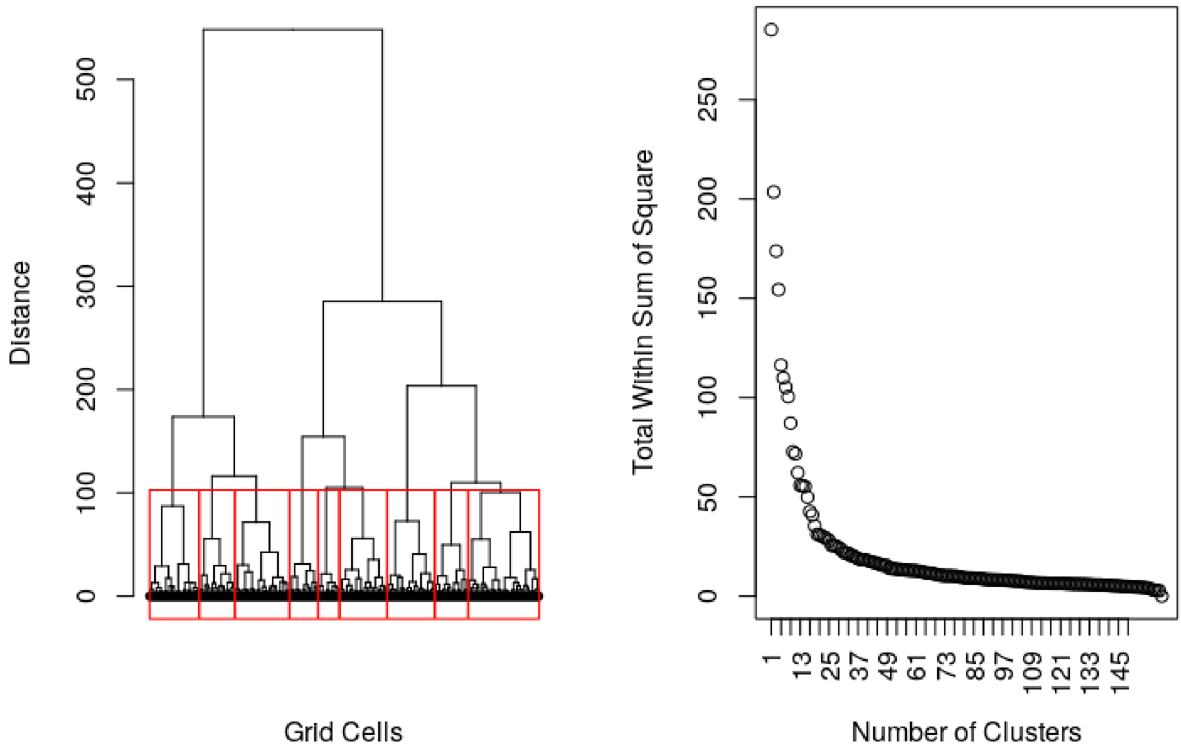

Figure 3.7: Cluster analysis results, using Ward's method with Euclidean distance on SPEI-3 values for the period July 1979 to December 2010, showing dendrogram with cluster boundaries (left) and elbow method results (right)

Having identified the SPEI-3 regions across New Zealand, the processes noted in Section 3.5 were repeated for each region. This process involved first identifying the number of drought events within each region above the SPEI-3 threshold of -0.8. This threshold is the same as that applied over New Zealand as a whole and introduces a limitation to the regional analysis in this thesis by potentially over or understating the characteristics of regional drought events. However, this was preferable to developing regional specific drought thresholds, as such a technique would make the methodology inconsistent across each region. The use of SPEI-3, standardised to each grid cell in each region, means that the use of different threshold values would not enable comparisons to be made between regions, nor enable individual regions to be identified as potentially driving drought occurrence when investigating the New Zealand wide drought events. Selecting a universal threshold value across each region means that regions with typically neutral to negative SPEI values (such as Central Otago) would have fewer drought events than if a regional specific threshold value was used (as the 10% threshold value across these regions would be more negative than the -0.8 SPEI-3 value selected). However, because drought is relative to each region, the New Zealand wide threshold value means that drought across each region can be directly compared back to the New Zealand wide drought events. Therefore, regions can be identified that drive these New Zealand wide drought events.

These regional drought events were then analysed, alongside the IVT associated with each drought event, which again included the two months leading up to drought detection under the SPEI-3. Mean conditions for all regional drought events and IVT associated with this mean were also calculated. Classification was then able to be performed on each region. Due to limitations in the extent of this thesis and to ensure conciseness, only the 90th quantile and January (representing summer) and July (representing winter) were selected for further analysis over all regions. However statistical testing was performed on all possible combinations, to ensure that the chosen categories (90th quantile, January and July) were representative of the quantiles and seasons.

The 90th quantile was chosen as the middle ground between the 95th and 80th quantile. The 90th quantile had the most regions showing statistically significant results in changes in IVT during drought (all regions except for Nelson/Marlborough, West Coast and Central Otago) (Table 4.23). Visual agreement was seen across most of the regions between all quantiles (Appendix B). Because the New Zealand wide analysis established the importance of summer and winter periods, with the largest and smallest changes occurring respectively (Figure 4.10; Section 4.4.3.2), these two seasons were chosen for further regional analysis. Within both seasonal periods, both January and July revealed the most statistically significant different IVT fields over the regions (Table 4.23). January and July were also visually representative of the other months within the respective season

(Appendix B). Therefore, collectively it was felt the 90th quantile, January and July were representative of the quantile and seasonal conditions across the regions. The full results of IVT for all regions, all months and all quantiles are shown in Appendix B.

The bounds of IVT for each statistical test was set to the same spatial extent as the regional bounds as identified by the cluster analysis on the SPEI-3 results, with some under-and over-lap as a result of the different grid size as noted in Section 3.5.3. The statistical testing performed on a regional level should be treated with caution for some regions due to the small sample size, a result of the coarse grid size resolution, which when applied over regions across New Zealand resulted in few spatial data points. Because some regions still had sufficient data points to enable a robust statistical test, the test was still conducted, however it must be noted that for regions like East Cape and Central Otago the statistical testing performed is likely invalid. As a result of the lack of spatial points, reference to those regions with insufficient data points is limited in Chapter 4 and Chapter 5, with the focus instead being on changes in the median values between the mean conditions and drought conditions. Only those regions with sufficient data points are discussed in reference to statistical significance in Chapter 4 and Chapter 5.

Finally, an analysis was also performed using the SOM technique. This involved investigating the relationship between the SOM nodes identified in Section 3.5.4 and their frequency of occurrence with SPEI drought months within each region. This relationship was further investigated by grouping the node occurrence based on the month, to investigate if any particular node occurred more frequently during a specific month of drought. Node occurrence during the top quantiles within each region was also investigated. Again, the process was the same as that outlined in detail under Section 3.5.4.

All calculations and visualisation of the SPEI-3 and IVT databases, the composite analysis and the SOM analysis were performed using the R software (R Core Team, 2019). Aside from the initial aggregation and filtering of data (performed using CDO operators (Schulzweida, 2019)), all analysis in this thesis was performed using the R software (R Core Team, 2019), with a list of packages being shown in Appendix D alongside a link to the reproducible code.

3.7. Summary

An SPEI dataset obtained via personal communication with the lead author of Stagge *et al.* (2015) is used to investigate hydrological drought over New Zealand and across regions (Figure 3.1). The analysis was performed on a three month time step, after investigating the existing literature on the performance of smaller accumulation periods and to aid in the assessment of these short accumulation periods which are used within the NZDI. Both an environment to cliamte and a climate to environment approach are used to analyse the relationship between atmospheric moisture and drought (Figure 3.1). Drought conditions and atmospheric moisture are both quantified using existing databases, and analysis is performed using composite maps (environment to climate) and a SOM (climate to environment) (Figure 3.1).

The SOM method represents a relatively new method of analysis for climate over New Zealand, by classifying IVT fields into similar patterns. Drought is defined using a threshold value identified as part of the preliminary analysis and was set at -0.8 SPEI-3, representing the top 10% national average drought events. Aggregation of drought events is performed by investigating mean drought conditions, representation of the 95th, 90th and 80th quantile of drought events and of each month associated with drought (Figure 3.1). Analysis is performed across New Zealand as a whole, and on a regional level after regional identification using Ward's clustering (Figure 3.1). Clustering is performed on the SPEI-3 time series of national average values, with nine regions being identified.

4. Results

4.1. Introduction

The preceding chapters have set forth the research objectives for this thesis (Chapter 1), by an exploration of the current state of research and literature in the field (Chapter 2). A methodology was then developed to achieve these research objectives (Chapter 3). The following chapter analyses the results of the application of this methodology. First, the sensitivity of the chosen SPEI dataset is reviewed (Section 4.2). Mean monthly IVT conditions witnessed over Australasia are then analysed (Section 4.3). Following this initial overview, New Zealand droughts are explored in greater detail (Section 4.4.2), including adopting an environment to climate approach (Section 4.4.3) and a climate to environment approach (Section 4.4.4). This process for examining New Zealand droughts is then repeated on a regional level (Section 4.5), having first identified nine distinct regions over New Zealand (Section 4.5.2).

4.2. Sensitivity Analysis of SPEI Accumulation Periods

To understand the sensitivity of the three month SPEI accumulation period (SPEI-3), the SPEI-3 was compared against the other accumulation periods from the Stagge *et al.* (2015) dataset. All accumulation periods are calculated across the time period from July 1979 to December 2010 and were developed using the same reference period from January 1970 to December 1999 (Stagge *et al.*, 2015). SPEI values at each grid cell were averaged across the entire time period. The one month accumulation period shows a uniform negative SPEI pattern across the country, with the emergence of stronger negative SPEI values across Central Otago from the three month accumulation period onwards (Figure 4.1). Central Otago becomes increasingly negative as the accumulation period increases, with the upper South Island and lower North Island also becoming increasingly negative across the 12 and 24 month accumulation periods (Figure 4.1).

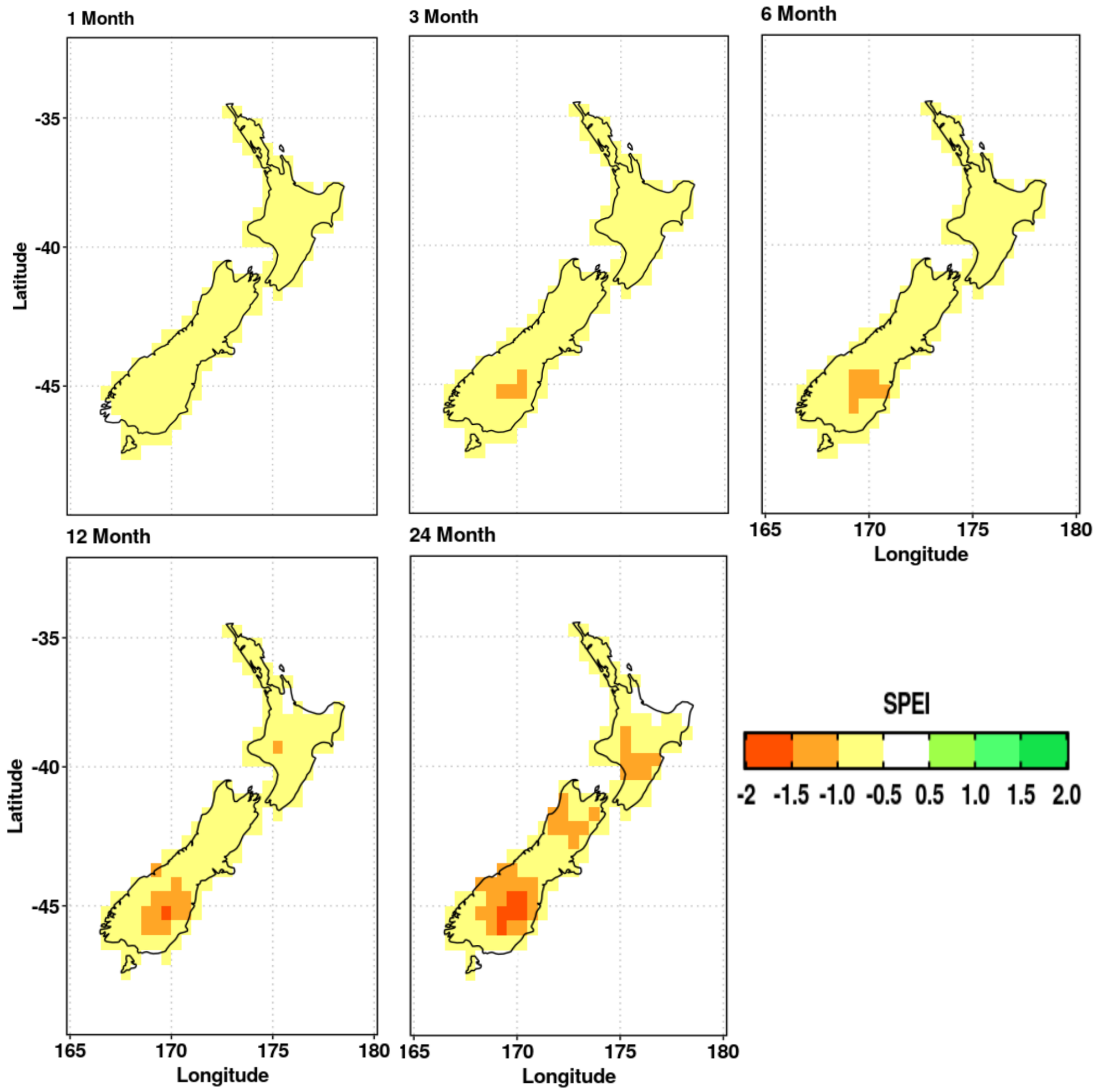

Figure 4.1: Mean SPEI across New Zealand for the period 1 July 1979 to 31 December 2010 (against the reference period of January 1970 to December 1999) for five accumulation periods

SPEI values for all grid cells were averaged for each month to generate a time series of national average SPEI values for each accumulation period. Mean SPEI over New Zealand shows decreasing monthly variability as the accumulation period increases (Figure 4.2). Opposingly, the range of variability increases as the accumulation period increases, with greater variability across the 12 and 24 month accumulation periods (Figure 4.2). In particular, these longer accumulation periods reveal greater variability across the second half of the time series, with a peak in SPEI values in the mid 1990s and a decline in SPEI values from the late 1990s to the early 2000s (Figure 4.2). The separation between accumulation periods appears greater during these peaks and troughs (Figure 4.2).

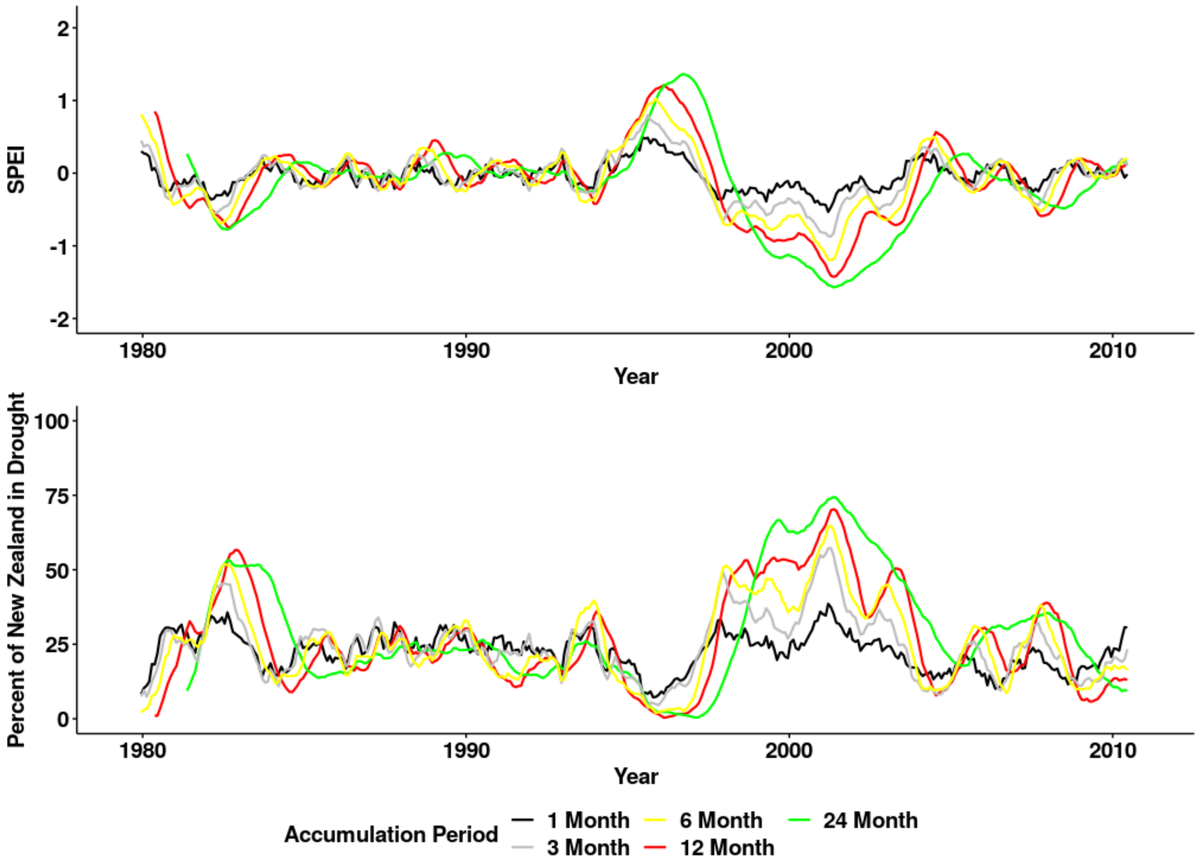

Figure 4.2: Time series of mean SPEI across New Zealand (top) and percentage of country in drought (bottom) for the period 1 July 1979 to 31 December 2010

Drought was defined as any month where the national average SPEI-3 fell below -0.8. This threshold level was applied to all accumulation periods (Section 3.4.3). Using this threshold, the time series of mean SPEI was converted into a percentage of the country in drought, by comparing the number of grid cells below -0.8 SPEI-3 against all grid cells across the time period. The percentage of the country in drought (Figure 4.2) shows a similar pattern to mean SPEI across New Zealand, with increases in drought coverage seen in the early 1980s and between the late 1990s and early 2000s (Figure 4.2). The lowest drought coverage is seen in the late 1990s, with no parts of the country in drought across the six, 12 and 24 month accumulation periods and 10% coverage under the one and three month periods (Figure 4.2). Accumulation periods show relative parity between the late 1980s and early 1990s, with approximately 25% drought coverage across the country (Figure 4.2). The greatest difference between accumulation periods is visible in 2001 (Figure 4.2). 2001 is also the year with the highest percentage of the country in drought, with 35% coverage under the one month accumulation period, increasing to 74% under the 24 month accumulation period.

4.3. IVT Characteristics over Australasia

IVT magnitude and direction was downloaded in 6 hourly time intervals for the time period July 1979 to December 2010, with monthly averages then calculated (Section 3.4.4). Each calendar month was then further averaged to calculate average monthly IVT conditions across the time series. To maintain a general overview of IVT conditions, the spatial bounds were left on the wider Australasian region.

Figure 4.3 shows regional IVT dominated by mid latitudes westerlies tracking over the Southern Ocean. A band of increased moisture flux progressively weakens to the south of New Zealand (-35°-55°S latitude) from May until October, moving equatorward during winter months, before growing from November through to April (Figure 4.3). IVT movement over New Zealand reveals a northwesterly flow when this band is weak between May and October (100-150 kg m^1 s^1), with a change to a west-northwest flow when the band is strong between November and April (250-300 kg m^1 s^1) (Figure 4.3).

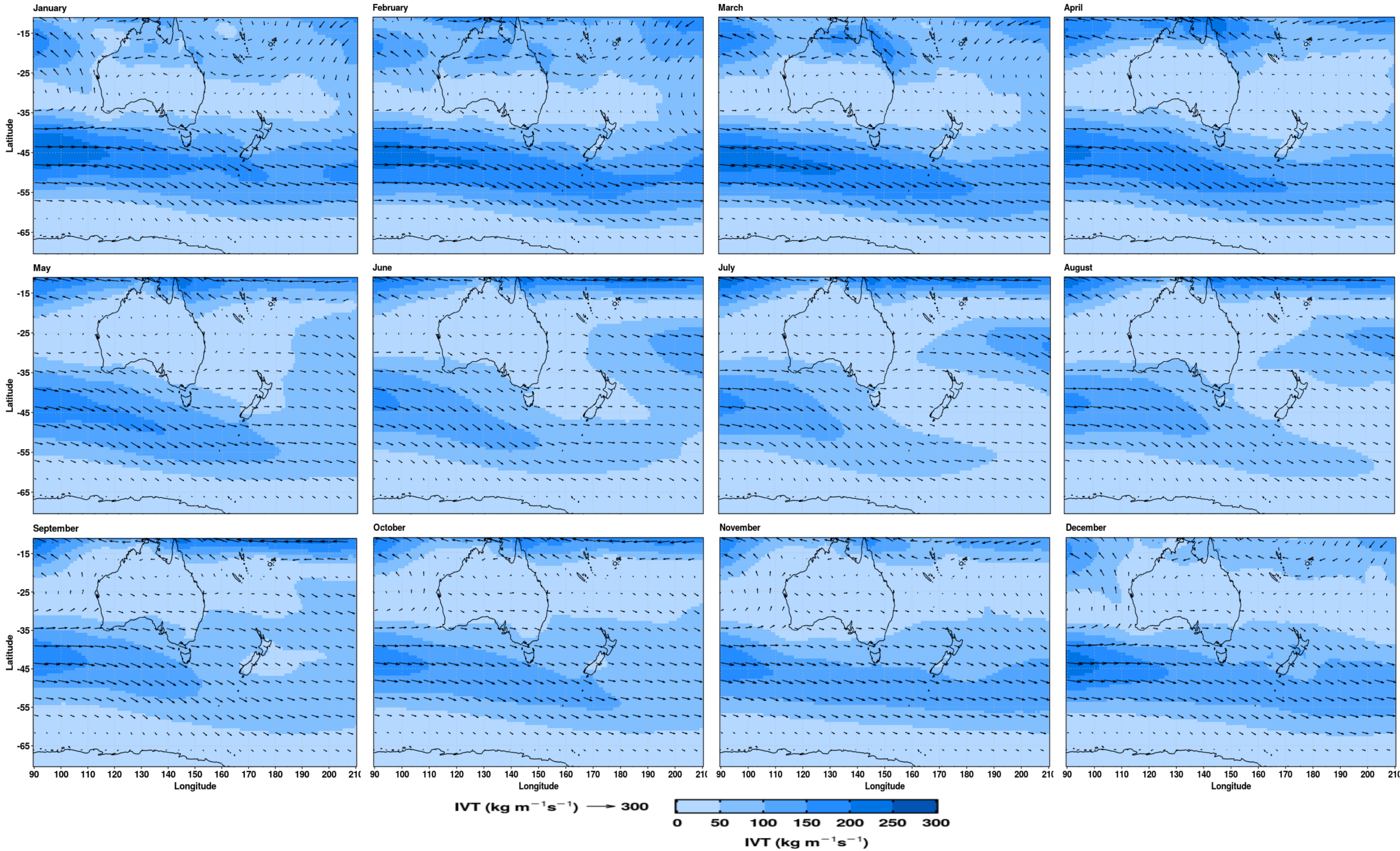

Figure 4.3: Mean monthly IVT magnitude and flow direction across Australasia for each calendar month over the period July 1979 to December 2010

4.4. New Zealand Drought Events

4.4.1 Introduction

The following section describes the analysis performed on both SPEI-3 and IVT values over New Zealand. Drought events are first identified by filtering the monthly time series of SPEI-3 values (from July 1979 to December 2010) to only reveal those months where the drought threshold value of -0.8 SPEI-3 is met, which represents the top 10% of SPEI-3 values (Section 3.4.3). This process resulted in a total of 22 unique drought events identified across New Zealand, encompassing 37 individual months. Analysis was then performed on these drought events, by first investigating the SPEI-3 of all these drought events as a mean. IVT associated with the same period was also analysed. Following this analysis, categorisation was performed using an environment to climate approach, by examining the top quantiles and drought conditions during each calendar month. Finally, a climate to environment approach is taken where the SOM technique is used to group IVT conditions across the time period (July 1979 to December 2010), before investigating the SPEI-3 conditions during each nodal period.

The differences in nomenclature when referring to drought events should also be reinforced before any further investigation of drought over New Zealand. As noted in Section 3.5.3, drought months are classed as either SPEI or IVT drought months. Only those months where SPEI-3 has exceeded -0.8 SPEI-3 are classed as SPEI drought months. IVT drought months include SPEI drought months plus the preceding two months. This is due to the 3 month accumulation period when using the SPEI-3. The process involved first identifying all relevant SPEI-3 drought months for the desired grouping (quantile, calendar month), before identifying the IVT drought months as all these SPEI drought months plus the preceding two months, with any duplication being removed. Thus, the analysis results in both SPEI drought months, and IVT drought months of roughly three times the number of SPEI drought months.

4.4.2 Characteristics of SPEI during New Zealand Drought Events

The 22 national drought events were ranked on drought severity, extent and duration. Drought severity was calculated as the total of all grid cell SPEI-3 values during the drought event. Drought extent was calculated as the number of grid cells in drought across the country during the drought event. Consecutive months in drought were also grouped, with the month with the highest severity and extent used to represent these multiple month drought events. A final ranking was then calculated as the sum of the ranked position for each of drought severity, extent and duration, with the tie-breaker being decided by drought severity. The drought covering the period August-October 1993 was ranked the highest drought event, being the most severe and of the largest extent (Table 4.1). The 22 drought events are made up of a total of 37 individual SPEI drought months, with 79 individual IVT drought months (Figure 4.4). The number of months in drought under SPEI and IVT are both spread over the entire calendar year (Figure 4.4). IVT drought months occur most frequently during autumn and early winter, while spring and early summer reveal the lowest number of IVT drought months (Figure 4.4).

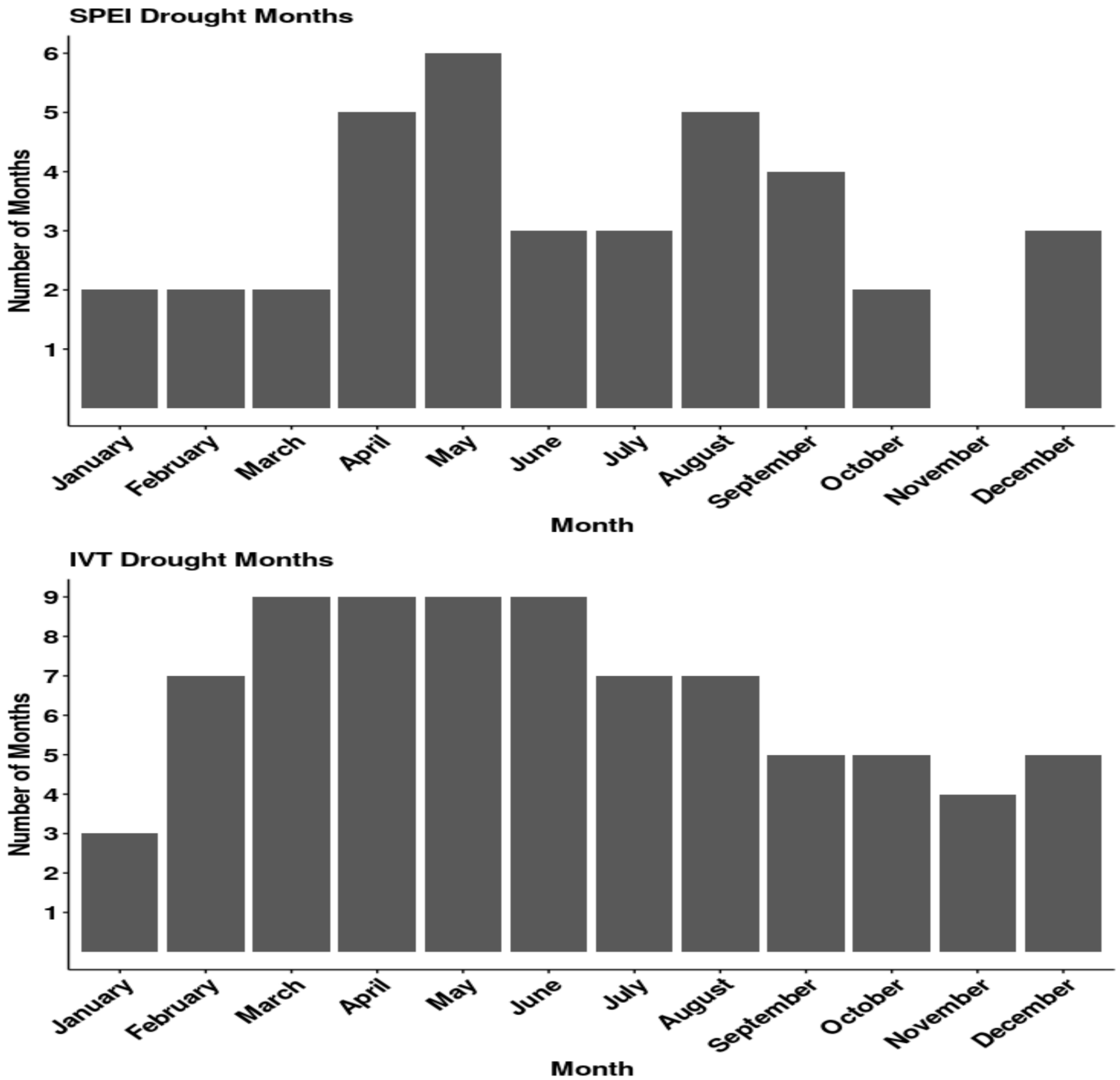

Figure 4.4: Total number of months in drought across New Zealand for the time period July 1979 to December 2010, showing both SPEI drought months (top) and IVT drought months (bottom)

Mean SPEI-3 values across all SPEI drought months shows widespread drought (SPEI-3 less than -0.8) over the entire country except for the east and north of the North Island (Figure 4.5). The strongest drought conditions are seen over the majority of the South Island and the south of the North Island, with SPEI-3 in the -1.5 to -2 category (Figure 4.5). To investigate IVT associated with these drought conditions, the IVT spatial boundaries were set to the immediate New Zealand region (165°-180°S latitude and -49°-32°E longitude), with this spatial extent kept for all further analysis. The average IVT magnitude across the associated IVT drought months shows strong decreases in magnitude over the North Island (approximately -70 kg m^{1} s^{1}), with smaller decreases seen over the lower South Island (approximately -30 kg m^{1} s^{1}) (Figure 4.5). Strong decreases in the westerly flow of moisture are witnessed over the North Island, with relatively little change in IVT direction over the South Island (Figure 4.5).

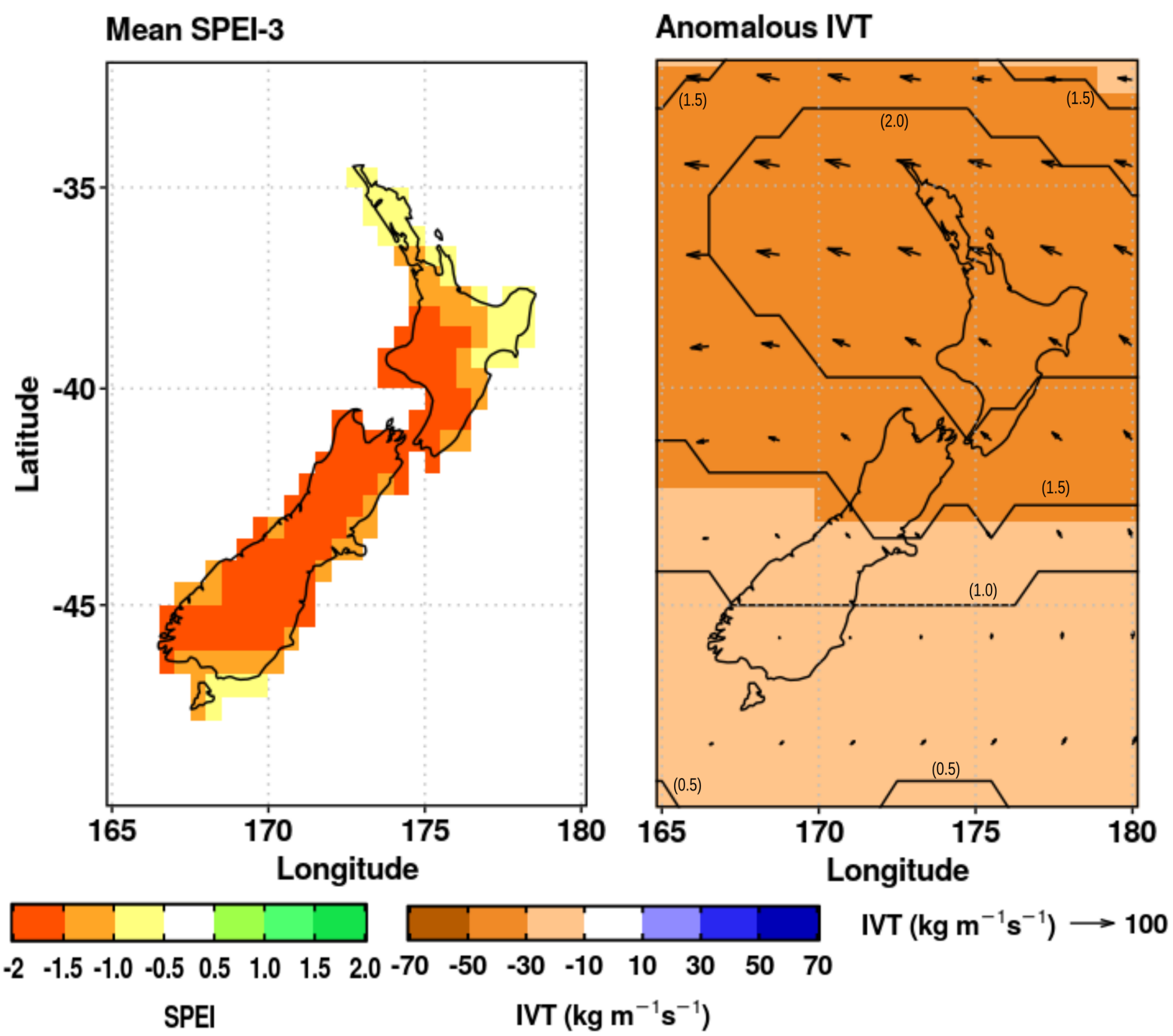

Figure 4.5: Mean SPEI-3 and Mean IVT anomalies over New Zealand during all drought events for the period July 1979 to December 2010. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction

Table 4.1: Drought events across New Zealand for the period 1 July 1970 to 31 December 2010, using drought severity, extent and duration to rank events from strongest to weakest

Date	Severity (SPEI)	Extent (Grid Cells)	Duration (Months)	Ranking
1993-08-15	-225.02	122	3	1
2001-07-15	-189.10	112	3	2
2001-03-15	-176.44	116	3	3
1982-04-15	-176.32	113	2	4
1985-04-15	-184.22	104	2	5
1992-05-15	-194.43	102	2	5
1991-07-15	-184.15	118	1	7
2000-12-15	-170.68	106	2	8
1987-08-15	-165.94	102	2	9
1985-10-15	-171.75	109	1	10
2002-05-15	-177.37	97	1	11
2010-04-15	-154.80	105	1	11
1999-01-15	-157.48	84	3	13
2010-12-15	-164.39	99	1	14
1997-07-15	-149.08	96	2	15
2003-04-15	-159.95	98	1	15
1998-05-15	-148.39	93	2	17
1986-12-15	-145.59	99	1	18
1989-09-15	-141.31	99	1	19
1981-02-15	-147.49	97	1	20
1984-06-15	-152.38	86	1	20
2000-08-15	-148.70	82	1	22

4.4.3 Environment to Climate Analysis

4.4.3.1 Quantile Analysis of SPEI

SPEI drought months were ranked using the same severity matrix as that used for drought events (Table 4.1), with the 95th (2 months), 90th (4 months) and 80th (8 months) quantile

SPEI drought months selected for further investigation. Because of the use of the same criteria, SPEI drought months predominately follow the same order and characteristics as that in Table 4.1 i.e. the top three SPEI-3 drought months are August, September and October 1993 (top drought event). The associated IVT drought months with each of these quantiles were also investigated, by interrogating the anomalous conditions associated with these IVT drought months. Under IVT drought months, there were a total of four (95th), eight (90th) and 13 (80th) drought months.

The top quantiles of SPEI drought months reveal the strongest negative SPEI-3 values across most of the North Island and both the upper and east coast of the South Island (Figure 4.6). SPEI-3 values weaken (move towards zero) across these areas as the quantile decreases (Figure 4.6). As the quantile range broadens, the spatial distribution of negative SPEI-3 values increases, in particular around the south Westland/Fiordland area (Figure 4.6). The SPEI drought months associated with the top quantiles occur predominately during spring and late winter, except for one month in early autumn (Figure 4.7).

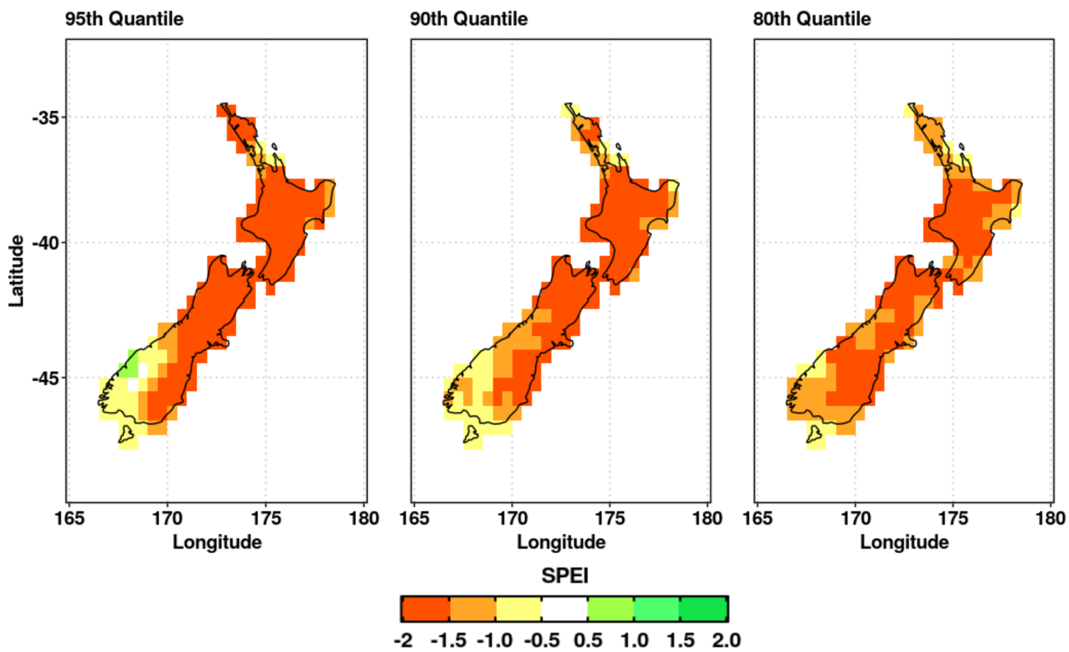

Figure 4.6: SPEI-3 over New Zealand during the 95th, 90th and 80th quantile SPEI drought months (ranked on severity, see Table 4.1) across the period July 1979 to December 2010

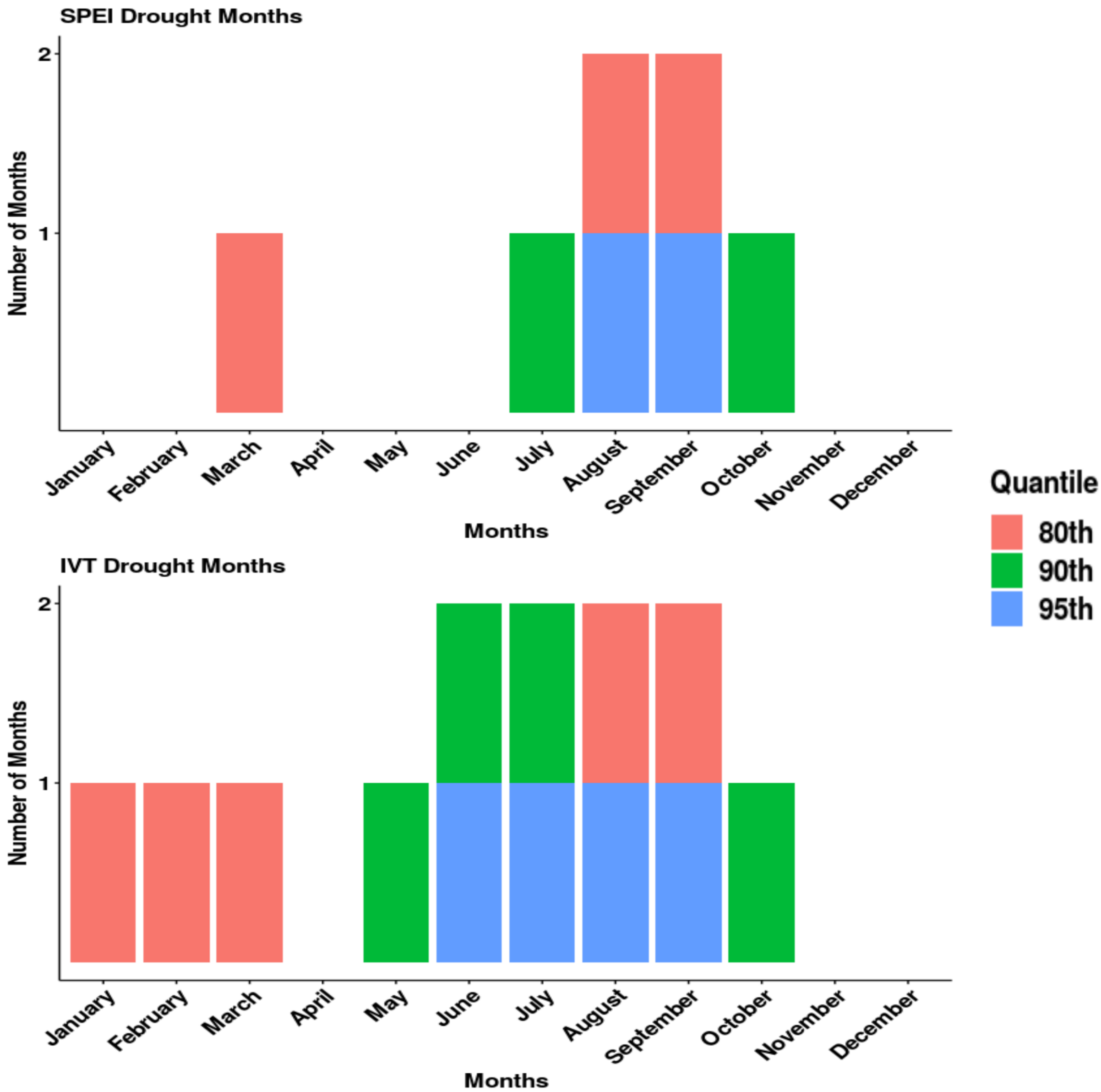

Figure 4.7: Occurrence of the 95th, 90th and 80th quantile drought months across calendar months for the period July 1979 to December 2010, showing SPEI drought months (top) and IVT drought months (bottom)

IVT drought months also show a clustering around spring, with an extension into the winter period associated with the spring dominance of SPEI drought months (Figure 4.7). IVT drought months also occur during the summer period, revealing the lead up conditions associated with the March SPEI drought month (Figure 4.7). IVT fields during the 95th, 90th and 80th quantile periods show anomalous decreases in moisture flux over the North Island, with the strongest decreases over the upper part of the island (Figure 4.8). The bottom half of the South Island shows neutral changes in IVT magnitude, with increased flux across Southland under the 95th quantile (Figure 4.8). As the quantile range broadens, the South Island shifts to reveal decreases in IVT magnitude flux (Figure 4.8). Associated with the decreases in moisture flux is a weakening of both the westerly and northerly components of moisture transport, with the strongest changes seen under the 95th quantile (Figure 4.8). The changes in domain averaged IVT magnitude are only significantly different from the 1979-2010 mean at the 95th quantile (Table 4.2).

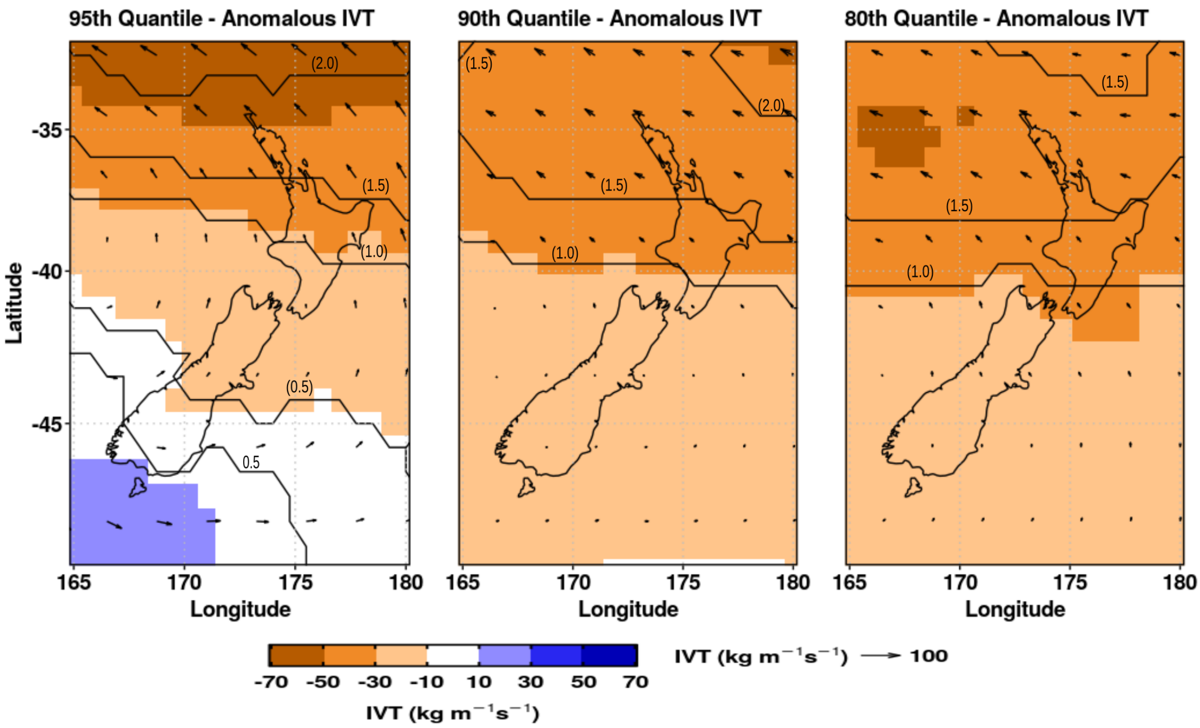

Figure 4.8: Anomalous IVT across New Zealand, categorised on the top quantiles of drought severity for the time period July 1979 to December 2010. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction

Table 4.2: Mann-Whitney U Test results on IVT values between various categorisations of drought events and mean conditions over the same period. Yellow highlighting signifies significance at the 95% level. Also shown is mean SPEI-3, distance from median value (50% quantile or mean monthly value) and the number of drought months for each category. Note no SPEI-3 drought months occurred in November

Categorisation	P-Value	Mean SPEI-3	Distance from 50% quantile or monthly time series average	Number of drought months
95th Quantile	0.00	-1.16	1.08	2
90th Quantile	0.50	-1.04	0.96	4
80th Quantile	0.18	-1.01	0.93	8
January	0.00	-0.80	0.92	2
February	0.50	-0.91	0.97	2
March	0.04	-0.97	0.95	2
April	0.00	-0.99	0.91	5
May	0.00	-0.99	0.84	7
June	0.00	-1.01	0.94	3
July	0.00	-0.91	0.84	3
August	0.00	-0.96	0.88	5
September	0.00	-1.08	0.97	4
October	0.00	-0.97	0.85	2
November	0.00	Nil	Nil	Nil
December	0.00	-0.98	0.98	3

4.4.3.2 Monthly Mean Analysis of SPEI

All SPEI and IVT drought months were grouped into the calendar month of occurrence. Average conditions were then taken for each calendar month, with IVT again analysed as anomalous conditions of IVT drought months.

All calendar months reveal strongly negative SPEI-3 values over most of the South Island, with the south and west of the island revealing weaker negative SPEI-3 values during August (5 SPEI drought months) and much of the east, south and west of the island during October (2) (Figure 4.9). The North Island reveals greater fluctuation in SPEI-3 values across the year, with positive values in East Cape and Northland during January (2), and neutral conditions during February (2) (Figure 4.9). Strongly negative SPEI-3 values are commonly seen over the lower North Island, with these strong negative values extending into the Waikato region during spring and early summer (Figure 4.9). SPEI drought months occur most often in late autumn, with another spike in occurrence during late winter and early spring (Figure 4.4). No SPEI drought months fell during November (Figure 4.4; Figure 4.9).

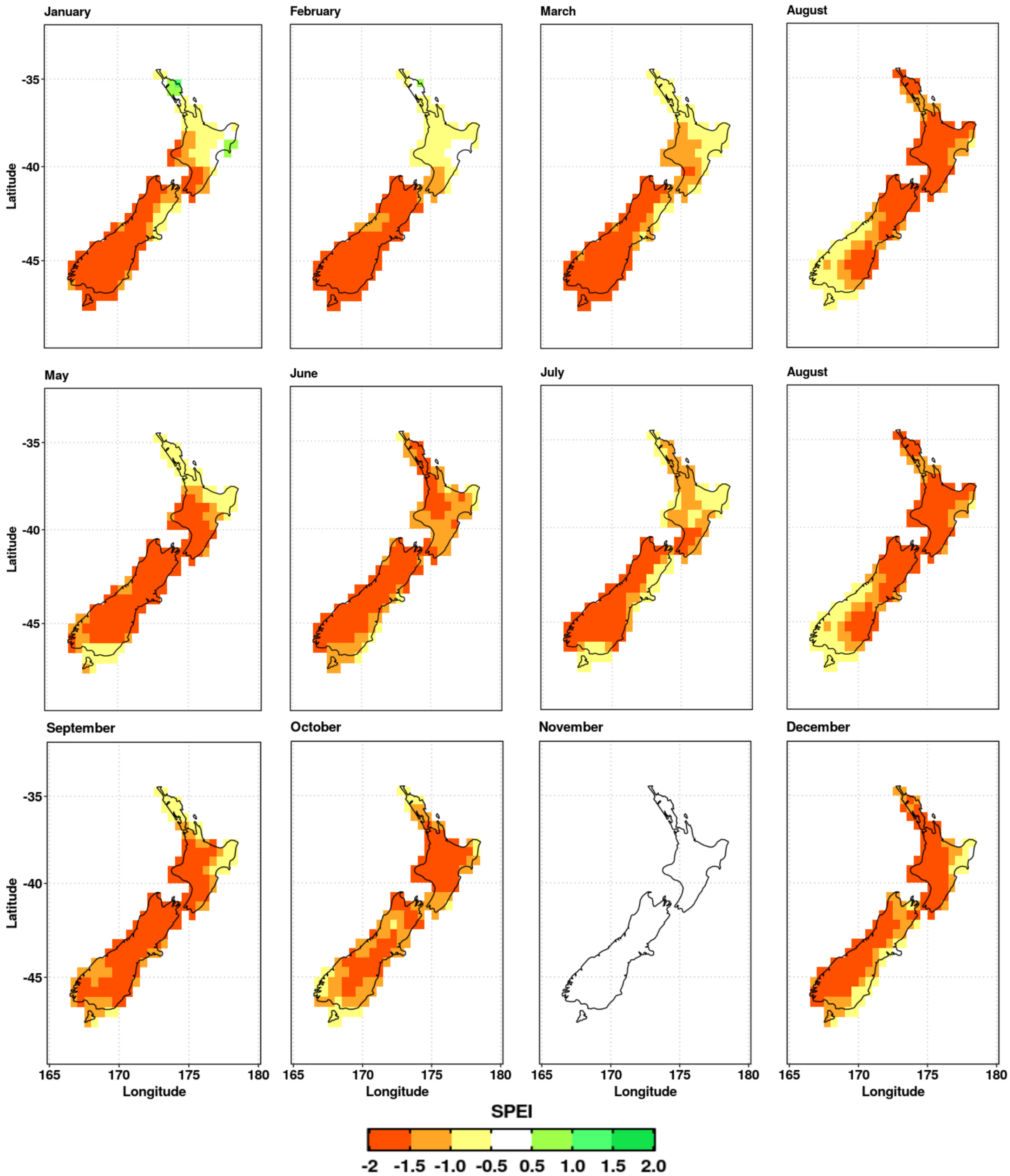

Figure 4.9: SPEI-3 conditions across New Zealand, categorised as an average of each calendar month in drought for the time period July 1979 to December 2010. Note that no droughts occurred in November under SPEI-3.

A weakening westerly component of moisture flow across the country is frequently visible during anomalous decreases in IVT magnitude (Figure 4.10). However the westerly component does show variation across calendar months, with a strong westerly decline associated with September events while a south easterly anomaly is associated with November events (Figure 4.10). Over New Zealand as a whole, IVT magnitude also reveals the strongest decreases during September and November (Figure 4.10). Regional variation is present, with the strongest decreases in magnitude and direction over the North Island during January (Figure 4.10). The strength of changes in moisture flux and direction vary during IVT drought months, with late summer months (January-March) showing strong directional changes and large variation in IVT magnitude across the length of the country (Figure 4.10). Particularly, while the majority of the country experiences decreased IVT magnitude, both the south and north of the country experience increased magnitude, with increased easterly/westerly anomalies to the north/south during January-March.

June highlights neutral IVT magnitude across the bottom of the South Island, with late autumn and winter (May-August) revealing minimal changes in direction and relatively weak magnitude declines over the South Island (Figure 4.10). Only the month of February was not statistically significant when testing changes in the IVT magnitude during IVT drought months against mean conditions during the same period (Table 4.2). Because statistical testing was performed on domain averaged IVT magnitude, the strong latitudinal variation (Figure 4.10) may explain the lack of significance for February.

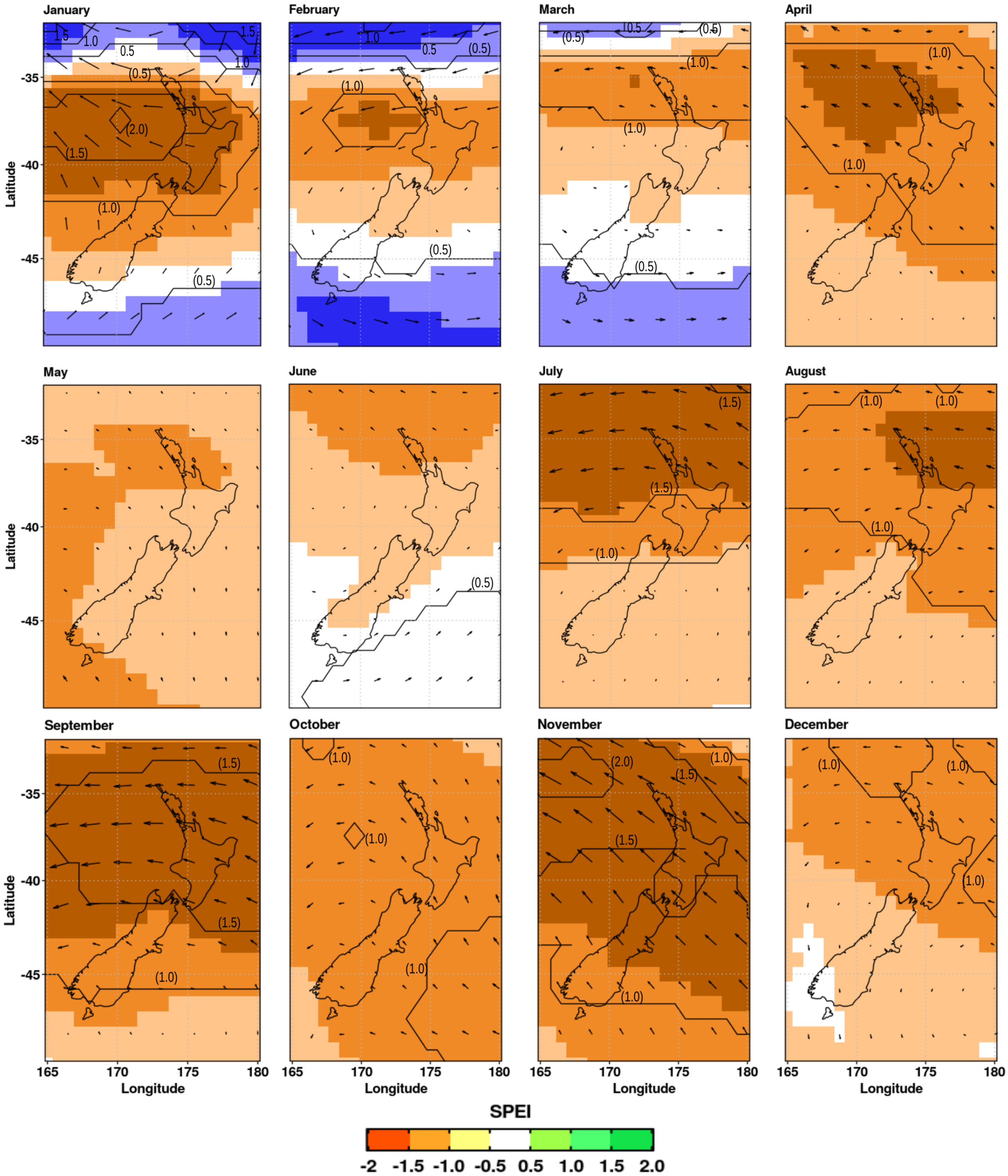

Figure 4.10: IVT anomalies across New Zealand, categorised as an average of each calendar month in drought for the time period July 1979 to December 2010. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction. Note May is entirely in the -0.5 to -1.0 range

4.4.4 Climate to Environment Analysis

The SOM technique is a neural network method which is used as part of a climate to environment approach in its deployment in this thesis. 25 nodes were identified using the method, which classified each month from July 1979 to December 2010 into one of the 25 nodes (Section 3.5.4). The use of the term nodes throughout the thesis is analogous to a cluster. Averages were then taken of anomalous IVT conditions and SPEI-3 conditions during each node. Following this, each node was analysed by investigating the frequency of occurrence of each calendar month drought events within it, as well as the number of top quantile months which fell within each node. This analysis involved an investigation of both SPEI drought months (month where SPEI-3 -0.8 threshold is exceeded) and IVT drought months (SPEI drought months plus the preceding two months).

What follows is an analysis of nodes 1, 3, 4, 5, 6, 9, 11, 16 and 25 that represent a range of conditions which occurred concurrently with IVT drought months across New Zealand as a whole and across selected regions. These were selected based on nodes concurrent with four or more IVT drought months, as well as selected nodes representing unique regional characteristics.

Nodes 1 and 6 (3 and 6 SPEI-3 drought months respectively) feature relatively strong declines in moisture flux over both islands, which is the most spatially consistent across the 25 nodal domain, with the upper North Island revealing lesser declines under node 6 (Figure 4.11; Table 4.3). They also feature declining westerly movement of moisture across the entire country, with node 6 featuring a stronger decline in the northerly flow alongside the westerly decline (Figure 4.11; Table 4.3). Both nodes indicate nationwide dry conditions, in particular across Central Otago and Abel Tasman under node 6 (Figure 4.12; Table 4.3). Late winter SPEI drought months predominately occur under node 6, while all SPEI drought months within the 95th quantile also occur under node 6 (Figure 4.13; Figure 4.14; Table 4.3). Node 1 also features the presence of SPEI drought months in the 80th quantile (Figure 4.14; Table 4.3).

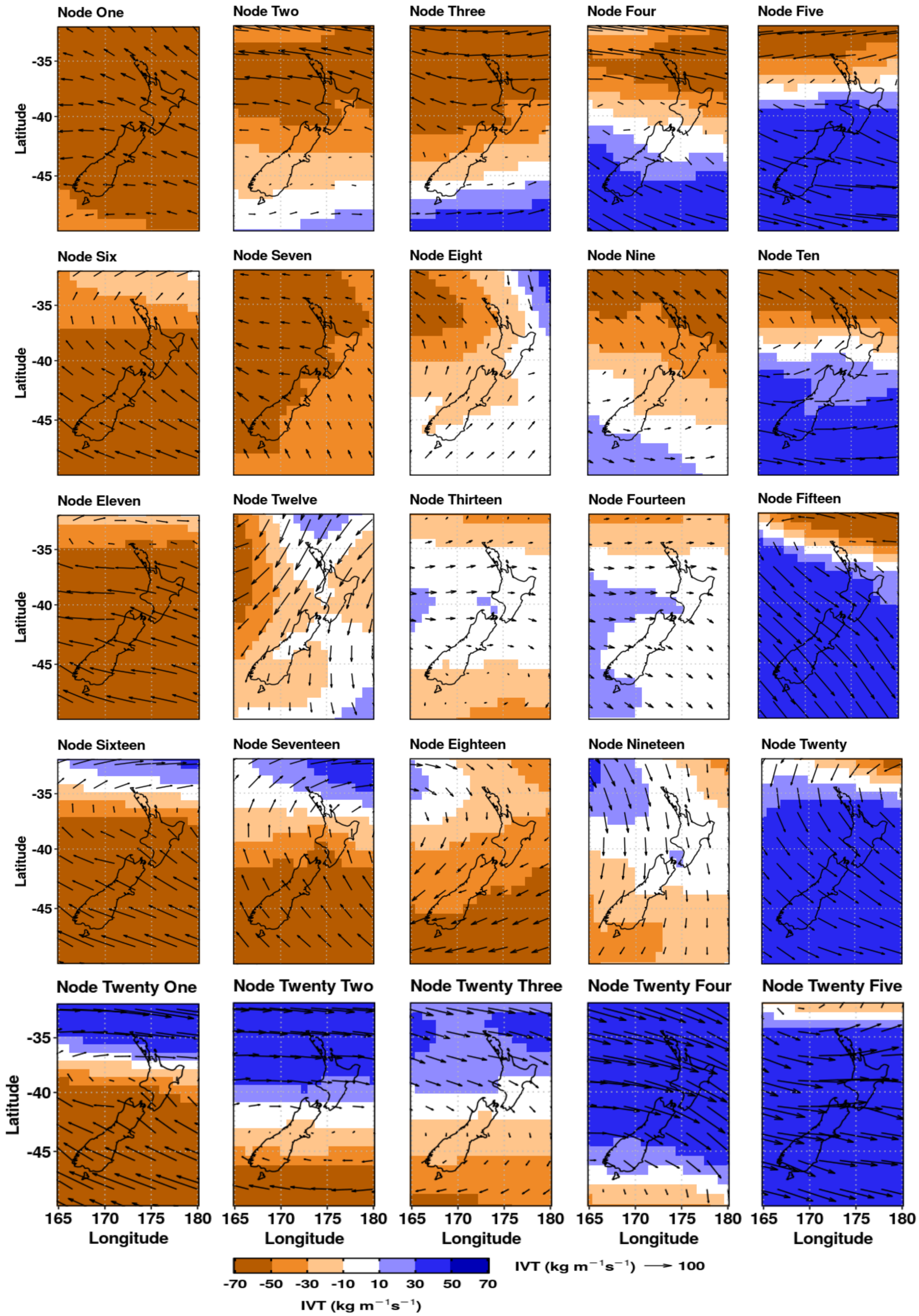

Figure 4.11: IVT anomalies associated with each SOM node, covering the period July 1979 to December 2010

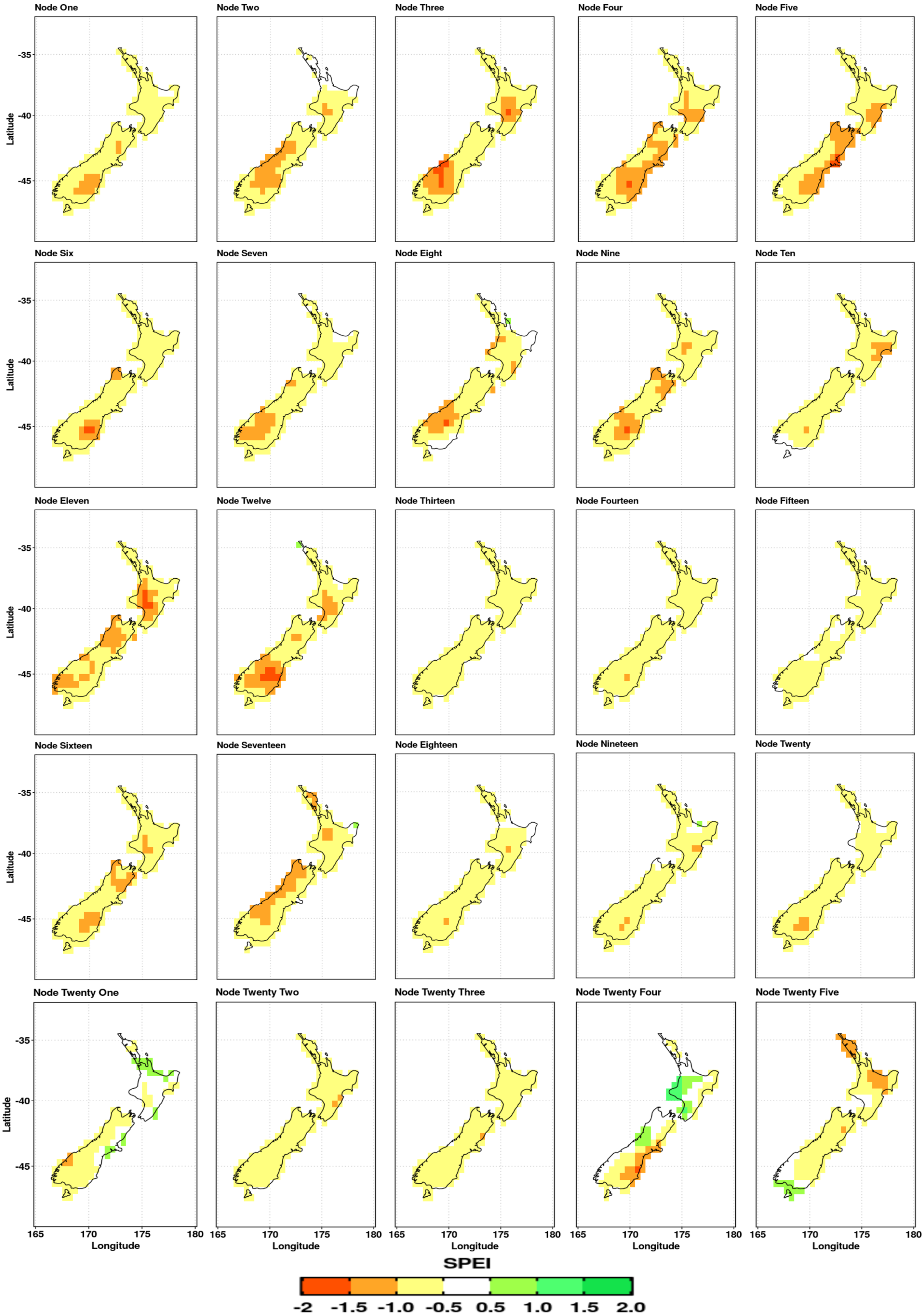

Figure 4.12: SPEI conditions associated with each SOM node, covering the period July 1979 to December 2010

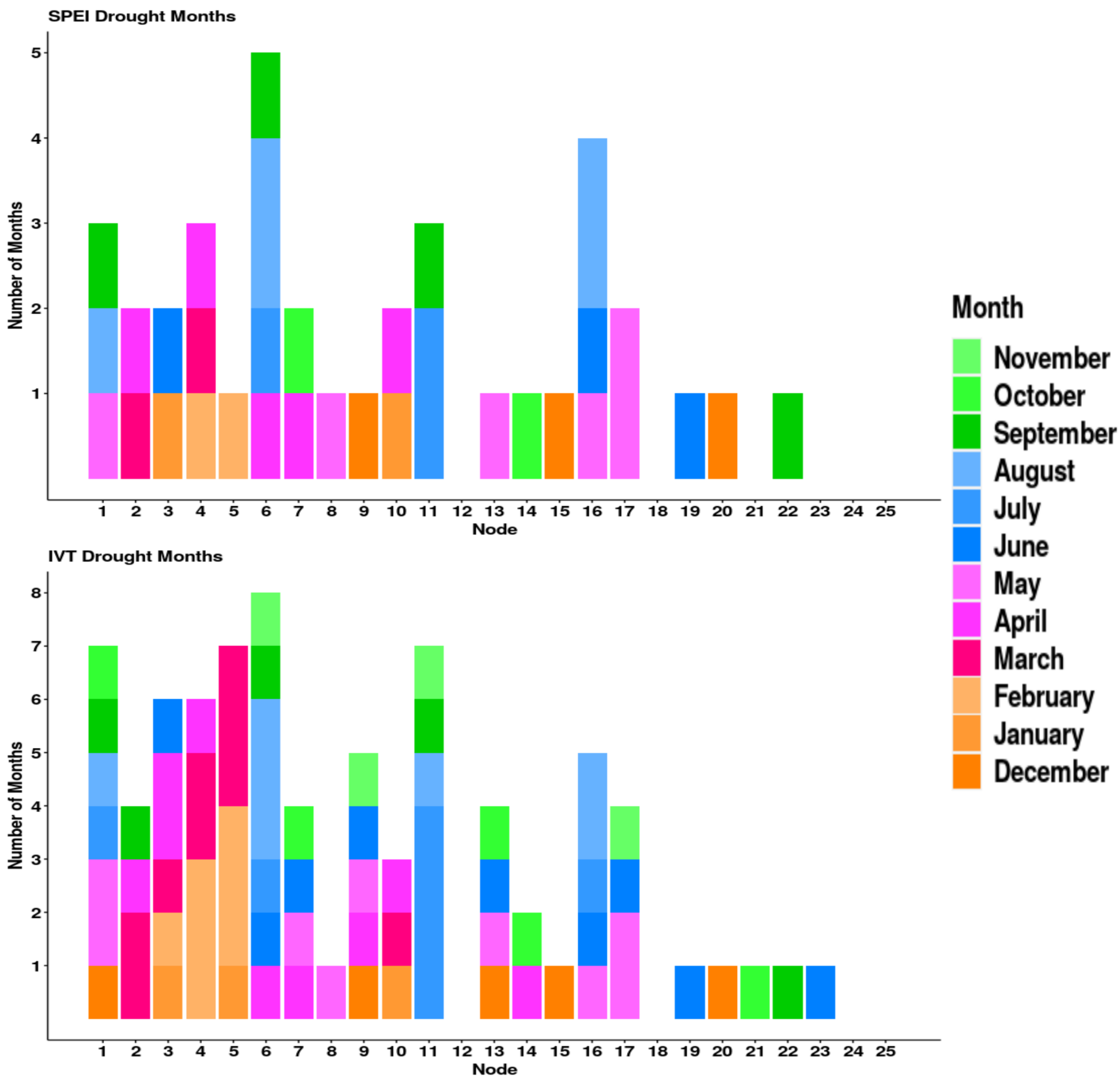

Figure 4.13: Frequency of SPEI drought months (top) and IVT drought months (bottom) during each SOM node, categorised by calendar month

Nodes 3, 4 and 5 feature a progression of increasing moisture flux moving south to north across the country (Figure 4.11). No change is seen in IVT magnitude across Southland under node 3, which under node 4 shifts to increased moisture flux (Figure 4.11; Table 4.3). Moving into node 5, this band of increased moisture flux moves from the bottom half of the South Island up to the middle of the North Island (Figure 4.11; Table 4.3). At the same time, the area of negative moisture flux decreases, moving from coverage over most of the country under node 3 to just the upper North Island under node 5 (Figure 4.11; Table 4.3). Directional fluxes follow those of the moisture flux, with increased moisture flux seen alongside increased westerly moisture movement, decreased moisture flux associated with decreased westerly moisture movement, and no change in directional movement associated with little change in IVT magnitude (Figure 4.11; Table 4.3).

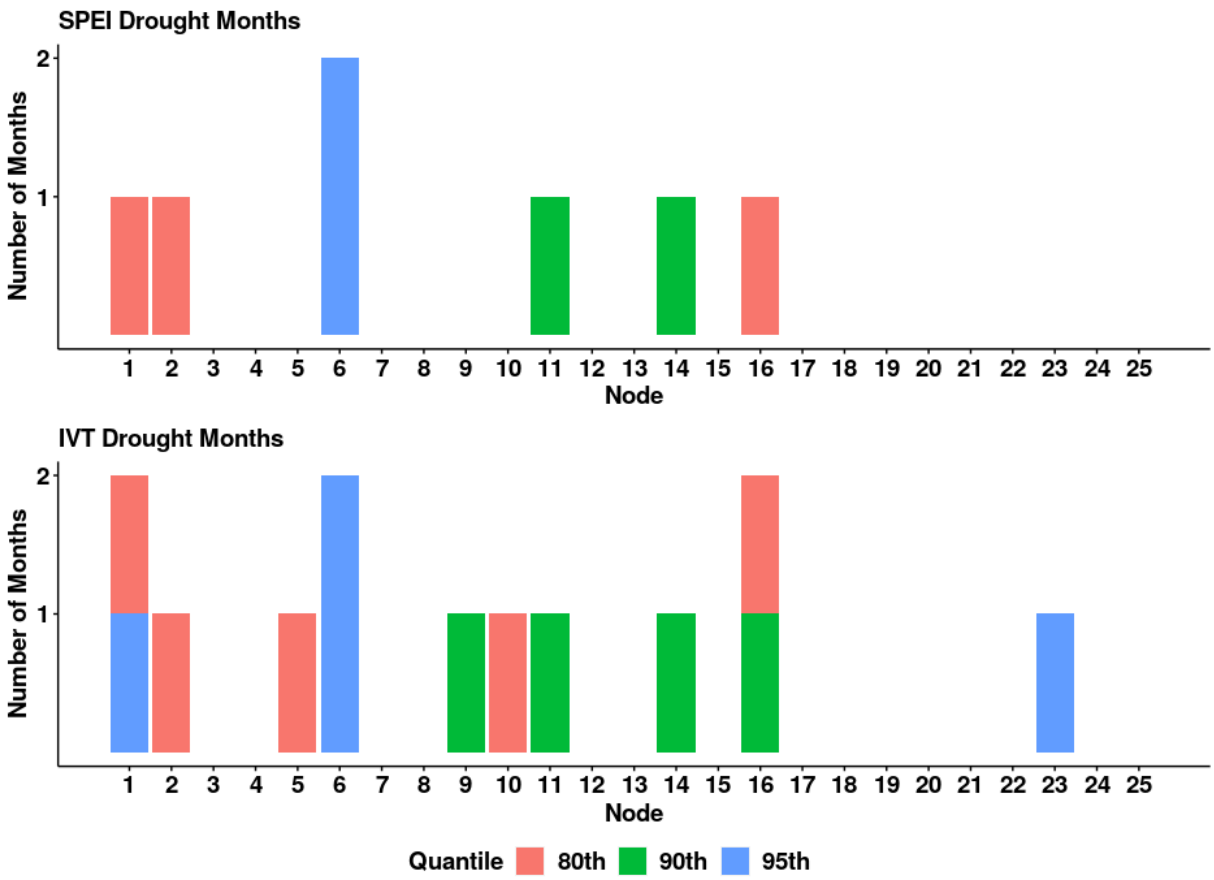

Figure 4.14: Frequency of SPEI drought months (top) and IVT drought months (bottom) during each SOM node, categorised by top quantiles

Nodes 3 and 4 reveal similar negative SPEI-3 values across the South Island, with Otago and the West Coast showing values below -1 SPEI-3 (Figure 4.12; Table 4.3). Node 4 covers more area of the East Coast as negative SPEI-3, while node 3 contains more negative SPEI-3 values (Figure 4.12; Table 4.3). Both nodes also reveal pockets of SPEI-3 values below -1 across the central North Island (Figure 4.12). Node 5 shows widespread weakly negative SPEI-3 values across the entire country but with more strongly negative SPEI-3 values on the east coast, especially of the South Island (Figure 4.12; Table 4.3). SPEI drought months do not feature heavily under node 3, with only two SPEI-3 drought months occurring during summer and winter respectively (Figure 4.13; Table 4.3). Both node 4 and 5 feature as significant nodes when investigating IVT drought months (6 IVT drought months and 7 IVT drought months respectively), but do not feature heavily when investigating SPEI drought months (3 and 1) (Figure 4.13; Table 4.3). SPEI drought months under nodes 4 and 5 occur during late summer and early autumn, with IVT drought months showing a similar pattern but to a larger extent (Figure 4.13; Table 4.3). No SPEI drought months in these nodes are present in the top quantiles, despite one IVT drought month in the 80th quantile featuring in node 5 (Figure 4.14; Table 4.3).

Outside of nodes 1 through 6, node 11 and 16 also feature as a regular co-occurrence with drought months over New Zealand (3 and 4 SPEI-3 drought months respectively). SPEI drought months occur predominately during late winter and early spring under both nodes 11 and 16, with two months being sufficiently strong to be present when investigating the occurrence of SPEI drought months in the top quantiles (Figure 4.13; Figure 4.14; Table 4.3). Node 11 is represented by very strong, consistent decreases in westerly flow alongside strong decreases in moisture flux over the entire country, with node 16 sharing similar characteristics apart from a smaller moisture flux decrease over the top of the North Island, alongside a slightly stronger southerly component to the easterly moisture direction anomaly (Figure 4.11; Table 4.3). SPEI-3 conditions reveal negative values across all of the country, with strong negative SPEI-3 values across central and western regions of the North Island under node 11 and weaker negative SPEI-3 values under node 16 (Figure 4.12; Table 4.3). While not featuring in the nationwide analysis, node 25 does warrant mention in its inclusion in Table 4.3, due to its significance on a regional level. Node 25 is characterised by dry conditions across the East Cape and Northland, with neutral values across Westland and positive values over Southland (Figure 4.12). IVT patterns reveal increased moisture flux and strengthening westerly moisture flow over the entire country (Figure 4.11). Node 25 is discussed further in Section 4.5.6.

Table 4.3: Summary of drought characteristics associated with SOM nodes that are associated with more than 4 IVT drought months

Node	IVT Anomalies	SPEI-3 Patterns	Seasonality	Quantile
1	Decreased westerly New Zealand, flux North Island.	Negative SPEI-3 South Island., Lower North Island	Late winter, early spring	90th, 80th
3	Decreased westerly North Island, flux New Zealand, Increased flux and westerly Southland	Negative SPEI-3, exception Auckland/Waikato, Northland	Autumn	None
4	Increased westerly New Zealand, exception Northland, increase flux South Island, decrease North Island	Negative SPEI-3 New Zealand wide, strong negative Central Otago	Late summer, early autumn	None
5	Increased westerly and flux New Zealand, exception Northland	Negative SPEI-3, exception Southland	Summer	80th
6	Decreased westerly New Zealand, flux South Island	Strong Negative SPEI-3 Central Otago, negative SPEI-3 rest of South Island, Lower North island and Northland	Winter	95th
11	Decreased flux and westerly New Zealand	Negative SPEI-3, exception Northland and East Cape	Winter	90th
16	Decreased flux and westerly New Zealand, exception Northland, Auckland/Waikato	Negative SPEI-3, exception Auckland/Waikato and East Cape	Winter	90th and 80th
25	Increased flux and westerly New Zealand	Negative SPEI-3 East Cape, Northland Positive SPEI-3 Southland	None	None

4.4.5 New Zealand Drought Events Summary

The mean SPEI-3 spatial field across all SPEI drought months highlights widespread drought over the entire country with the exclusion of the east and north of the North Island. Strong decreases in IVT are seen over the North Island alongside strong westerly IVT direction declines. Weaker declines in flux and westerly direction are witnessed across the South Island. Top quantile events occur predominately during later winter and early spring, with the composite SPEI conditions during the top quantiles mimicking those of the mean conditions, except for a wetter Westland and Southland region under the top quantiles. Similarly, IVT fields during the top quantile events are similar to the IVT fields under mean drought conditions, with a general weakening of the magnitude flux and direction as progression is made from the 95th to the 80th quantile.

IVT Drought months occur most frequently in the late autumn, early winter period and are represented by widespread negative SPEI-3 values across the country, with more positive values over the upper North Island. The greatest fluctuation in SPEI-3 values and IVT magnitude and direction is seen during summer droughts, with winter drought events showing the least amount of change in SPEI-3 and IVT magnitude and direction across the country. Nodes 1, 2, 3, 4, 5, 6, 9, 11 and 16 represent the most commonly occurring nodes during drought events over New Zealand (Table 4.3). These offer a range of IVT and SPEI conditions, from decreased westerly moisture flow and magnitude under nodes 11, to increased westerly direction and magnitude over the South Island under node 4 (Table 4.3). These nodes occur across all seasons and are represented in all of the quantile ranges (Table 4.3).

4.5. Regional Drought Events

4.5.1 Introduction

The following section describes a regional analysis of both SPEI-3 and IVT values across New Zealand. This process mimics that performed across New Zealand as a whole, with the same environment to climate and climate to environment approach adopted across all regions. First, regions were identified using Ward's clustering, before the time series of SPEI-3 was examined across each of the regions. This time series was then interrogated to identity drought events, being any month where SPEI-3 values fell below -0.8 SPEI-3. To keep the methodology in this thesis consistent, the same SPEI-3 drought threshold of -0.8 SPEI-3 identified nationwide was used for the regional analysis, creating an absolute threshold for regional analysis. This does result in a higher number of months in drought across some regions than the 10% threshold used in the nationwide analysis, as the small number of grid cells on a regional basis resulted in drought events of much longer duration than when viewed on a nationwide basis. This feature of the analysis should be taken into consideration when investigating the regional characteristics of drought, as the application of the same absolute threshold value (-0.8 SPEI-3) across all regions is not representative of the true top 10% of events in that region.

Having identified drought events across each region, mean spatial patterns during drought conditions for both SPEI-3 and IVT were able to be represented. Categorisation using an environment to climate approach then follows, by examining the mean IVT and SPEI-3 spatial patterns across the most severe drought events and calendar months, before a climate to environment approach is adopted where regional SPEI and IVT drought months are investigated against the IVT nodal scheme developed in Section 3.5.4. Due to size restraints in the present study, only the 90th quantile, as well as January (representing summer conditions) and July (representing winter conditions) were selected for further analysis.

4.5.2 Cluster Analysis of SPEI

To enable identification of regions across New Zealand, Ward's clustering was performed on the SPEI-3 values across New Zealand for the period July 1979 to December 2010 to identify clusters of similar values. The cluster analysis identified nine distinct regions over the country. An analysis using six regions was also performed for comparison with previous work (Kingston and Treadwell, in press) (Section 3.6). The nine identified regions are in order from north to south: Northland, Auckland/Waikato, East Cape, Lower North Island, Nelson/Marlborough, West Coast of South Island, East Coast of South Island, Central Otago and Southland (Figure 4.15). For simplicity, both the West Coast of the South Island and the East Coast of the South Island will henceforth be referred to simply as West Coast and East Coast. The difference between the six regional clustering and the nine regional clustering was the separation of regions over Central Otago, Nelson/Marlborough and Northland.

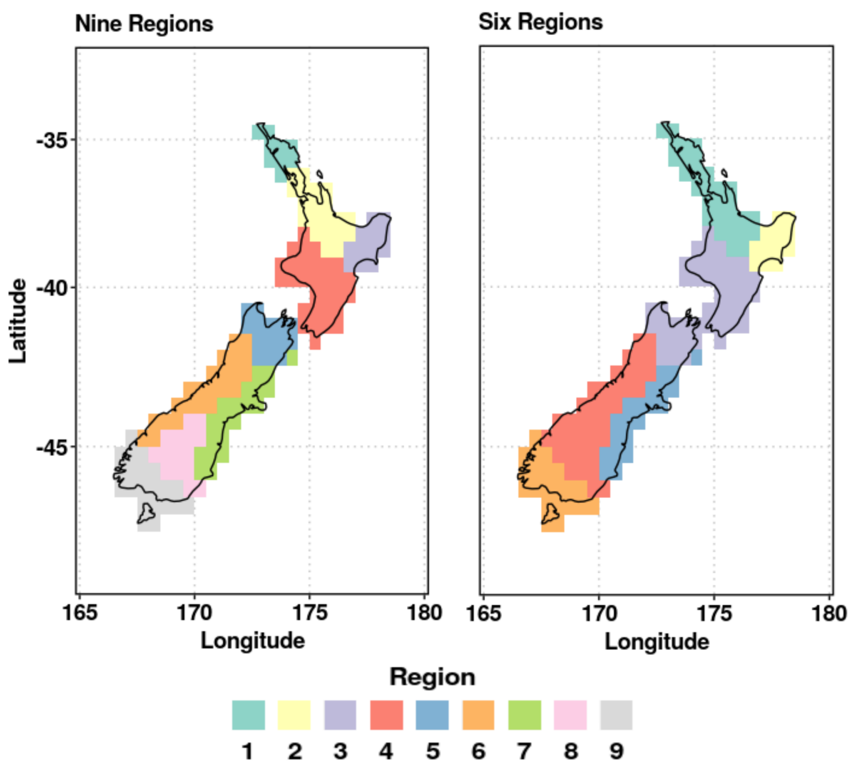

Figure 4.15: Cluster analysis results on SPEI values over New Zealand for the period 1 July 1979 to 31 December 2010, showing identification of nine (left) and six (right) regions

4.5.3 Regional Analysis: SPEI Conditions Across Regions

Regional mean SPEI-3 time series were smoothed to facilitate identification of general differences, with noticeable changes in SPEI-3 occurring in the 2000s over East Cape (increase), and Central Otago (decrease) (Figure 4.16). Other key differences between regional mean time series include the mid to late 1990s, showing declines in SPEI-3 values over the Lower North Island, Nelson/Marlborough and the East Coast (Figure 4.16).

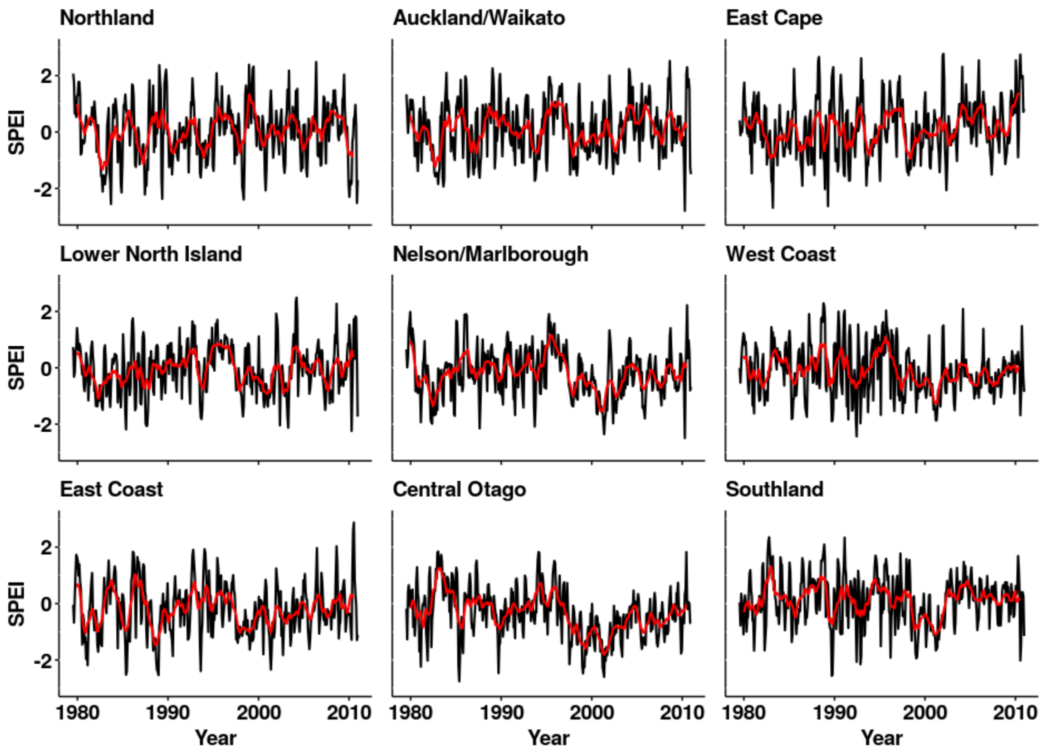

Figure 4.16: Time series of mean SPEI-3 for each region over New Zealand for the period 1 July 1979 to 31 December 2010. The red line denotes a time series smoothed on a 12 month rolling window

The percentage of regions in drought shows more clearly changes in the drought characteristics of each region, with peaks in drought coverage during the 1980s witnessed over Northland, Auckland/Waikato, East Cape, Lower North Island and Nelson/Marlborough (Figure 4.17). The 1990s highlight a period of relative stability, with no significant peaks in drought coverage across the regions, before significant spikes in drought coverage in the late 1990s/early 2000s across all regions except for Northland (Figure 4.17). Mean drought coverage ranges from 17.22% over Southland to 31.92% across Central Otago. East Coast and Nelson/Marlborough (29.26% and 27.48%) also feature with high mean drought coverage. Similar to the nationwide findings (Figure 4.2), drought coverage is highest during the 2001 period for all South Island regions, with 100% coverage reached across all South Island regions during 2001 (Figure 4.17). Northland, Auckland/Waikato and the Lower North Island all show the highest drought coverage in the spring of 1982, with 100% coverage reached throughout September and October (Figure 4.17). Again, these regional findings appear to drive the peak in nationwide drought coverage seen in 1982 (Figure 4.2). Except for the East Coast, the period with the lowest drought coverage across all regions is the mid 1990s (Figure 4.17), similarly witnessed when viewing the nationwide time series in Figure 4.2.

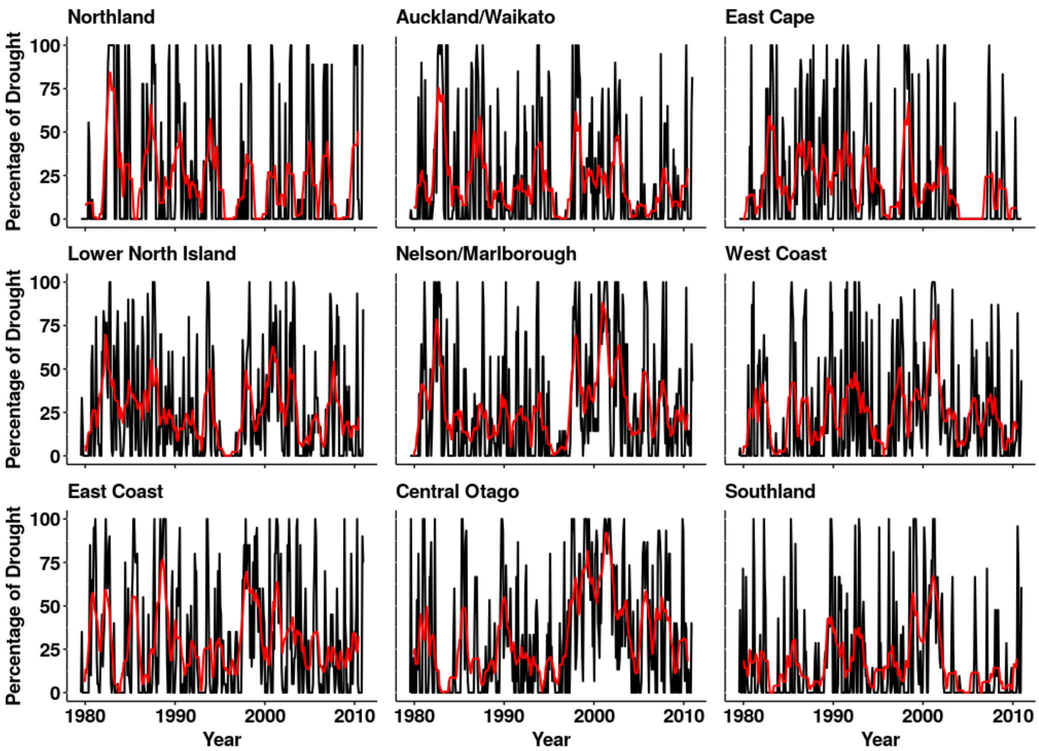

Figure 4.17: Time series of percentage of regions in drought (as defined in Section 3.4.3) for each region over New Zealand for the period 1 July 1979 to 31 December 2010. The red line denotes a time series smoothed on a 12 month rolling window

Applying the drought threshold to the SPEI-3 time series across each region identified a range of droughts in each region. These were again ranked according to the criteria established in Section 4.4.2, being drought severity, extent and duration. Table 4.4 highlights the highest ranked drought event across each of the categories, within each region. The number of drought events identified varies from the lowest in Northland and Southland to the highest over the Lower North Island (Table 4.4). Broadly, there is an increase in both the number of SPEI and IVT drought months across the South Island regions relative to the North Island regions, except for Southland (Figure 4.18).

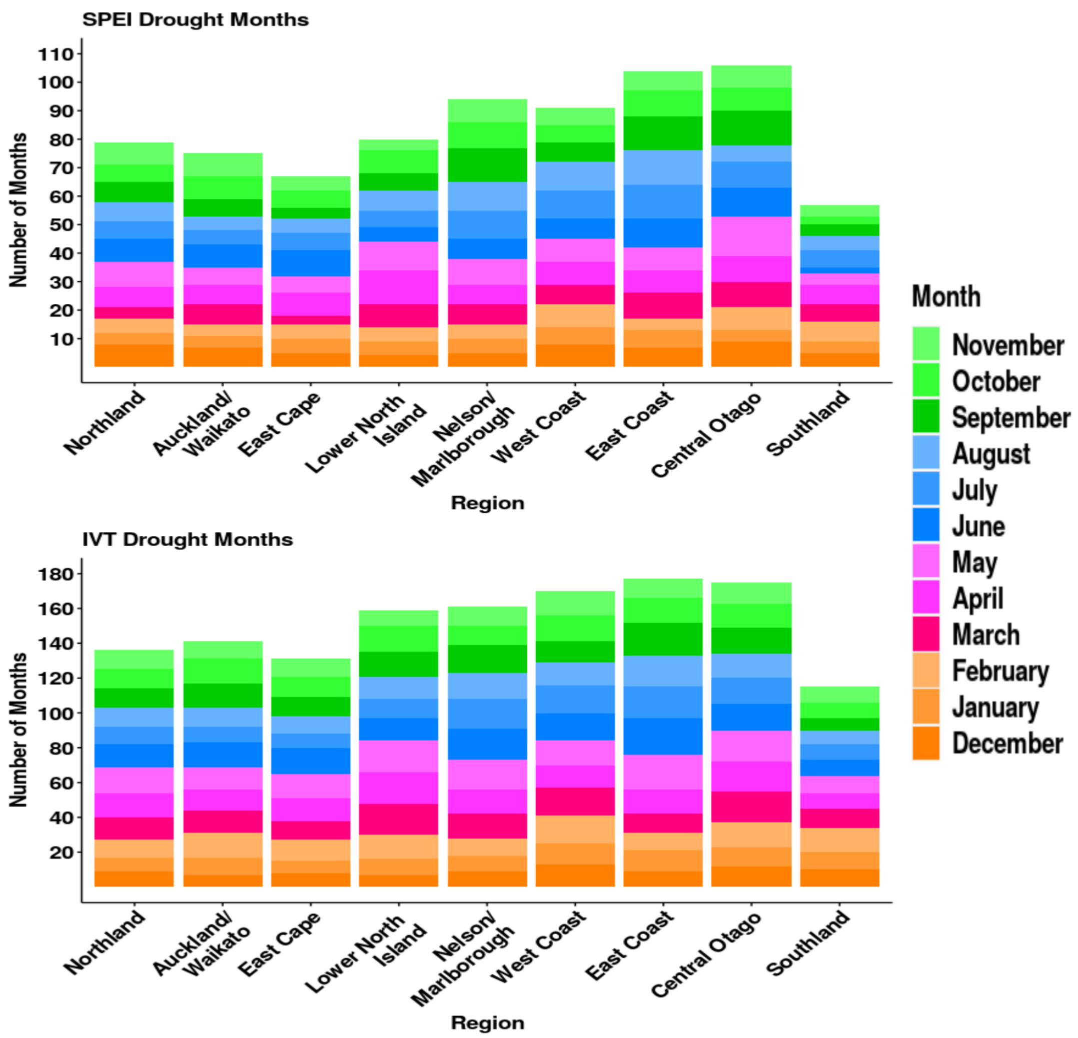

Figure 4.18: Total number of months in drought for nine regions across New Zealand (See Section 4.5.2) for the time period July 1979 to December 2010, showing both SPEI drought months (top) and IVT drought months (bottom)

Table 4.4: Regional table showing the number of drought events per region for the period 1 July 1979 to 31 December, alongside the highest ranking drought based on the severity, extent and duration of droughts within each region

	Number of Events	Max Severity (SPEI)	Max Extent (Grid Cells)	Max Duration (Months)
Northland	31	-28	11	11
Auckland/Waikato	34	-84	30	9
East Cape	32	-32	12	7
Lower North Island	42	-103	43	6
Nelson/Marlborough	37	-113	31	15
West Coast	41	-59	25	7
East Coast	40	-81	32	10
Central Otago	40	-77	28	14
Southland	31	-56	26	7

4.5.4 Regional Analysis: Mean Drought Events

The identified drought events for each region were then averaged to establish the mean conditions of SPEI-3 during drought within each region, before examining anomalous IVT conditions associated with the same time periods. Strong drought conditions within each region are commonly associated with slightly weaker negative SPEI-3 values across much of the rest of the country. The exception to this is Southland, where the East Cape remains in a neutral position (Figure 4.19). Across all regions, IVT directional anomalies are weaker than those seen across the nationwide averaged events (Figure 4.5; Figure 4.20). Weak decreases in northerly moisture direction are witnessed over Northland and Auckland/Waikato (Figure 4.20). Weak declines in westerly moisture direction is present over the Lower North Island and the West Coast, with slightly stronger declines across Southland (Figure 4.20). No directional anomalies are seen over East Cape, Nelson/Marlborough, East Coast and Central Otago (Figure 4.20). Northland, Auckland/Waikato, Nelson/Marlborough, East Coast and Central Otago all feature small declines in moisture flux over the region during drought events, while the Lower North Island, West Coast and Southland regions feature slightly stronger moisture flux declines (Figure 4.20).

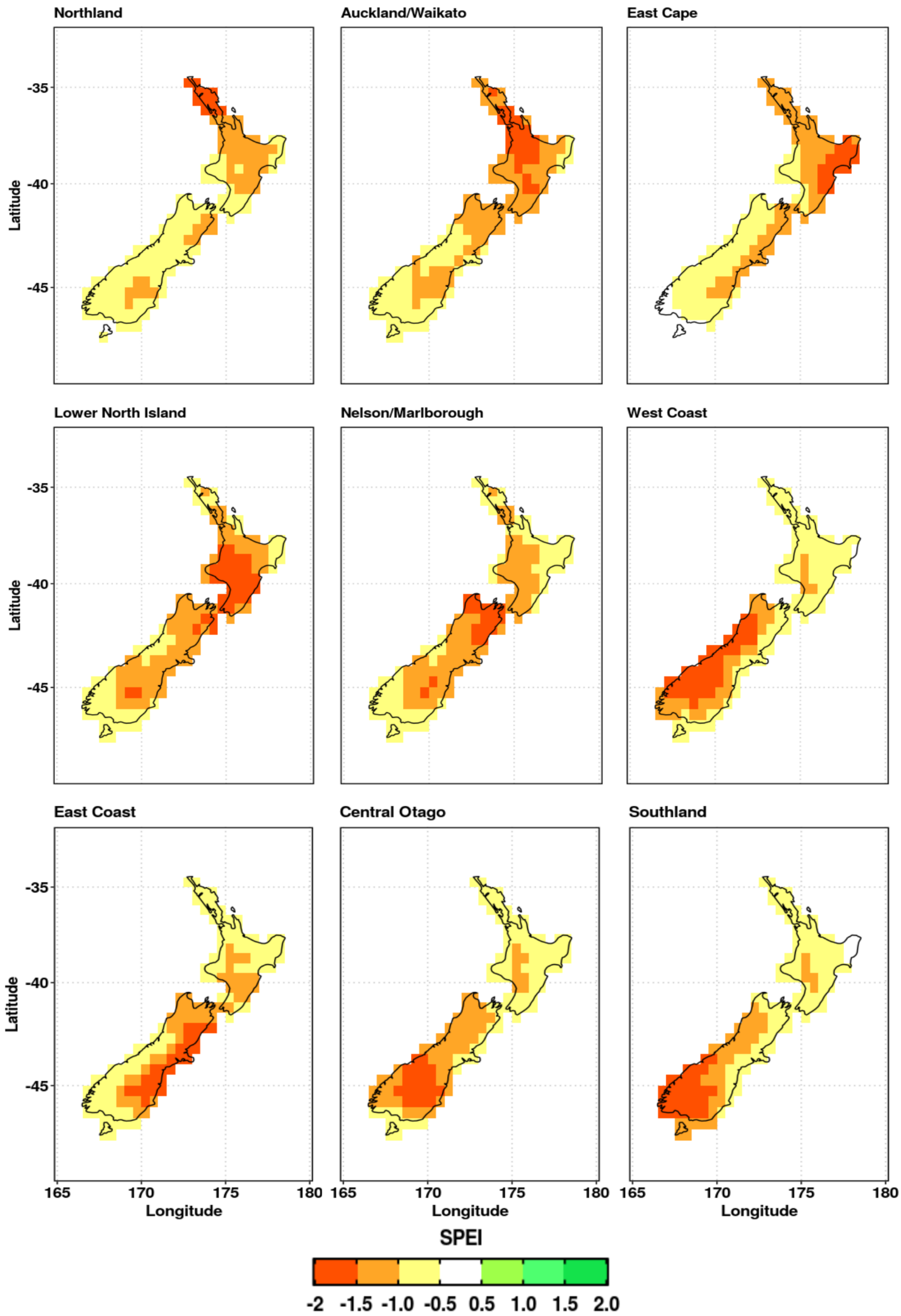

Figure 4.19: Mean SPEI-3 conditions during all regional drought events, for all nine regions, for the period July 1979 to December 2010

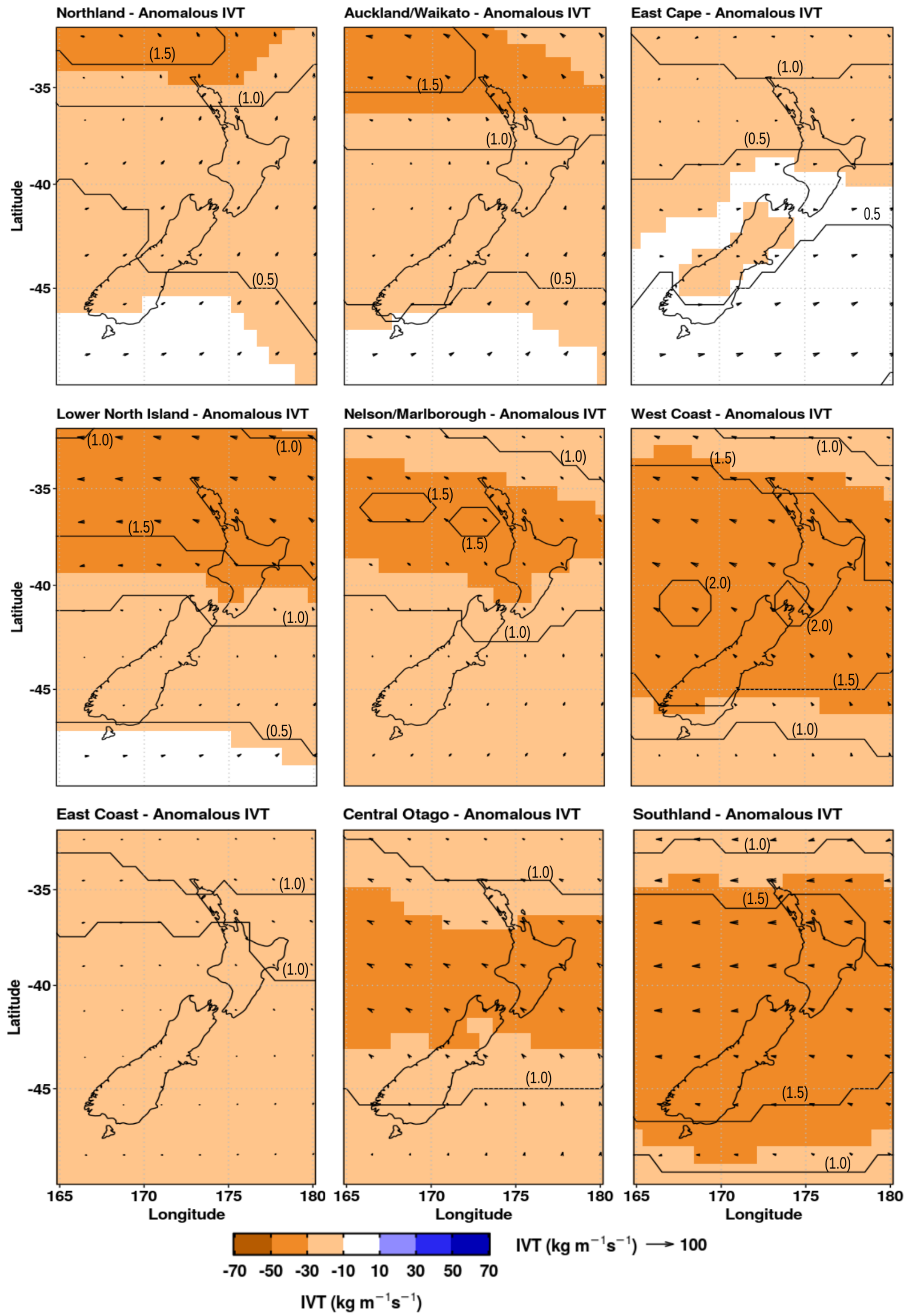

Figure 4.20: Mean IVT anomalies during all regional drought events, for all nine regions. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction

4.5.5 Regional Analysis: Environment to Climate

4.5.5.1 Quantile Analysis of Regional SPEI

For ease of comparison, only the 90th quantile droughts for each region were examined, as representative of the mid-point in extremes examined on a national level. This is discussed further in Section 3.6. Anomalous IVT conditions associated with the 90th quantile months were also investigated. The 90th quantile reveals widespread declines in moisture flux across all regions, except for Auckland/Waikato and East Cape (Figure 4.21).

Directional anomalies reveal decreased westerly flow over the Lower North Island and Southland, with increase/decrease southerly moisture direction across the West Coast/East Coast (Figure 4.21). Little directional change is witnessed across Nelson/Marlborough and Central Otago (Figure 4.21). Decreases in the northerly flow of moisture are visible across Northland and Auckland/Waikato, with no change in magnitude across Auckland/Waikato (Figure 4.21). Uniquely, the 90th quantile across the East Cape reveals increased westerly direction anomalies and moisture flux (Figure 4.21). Deviation between the 90th quantile and mean conditions is seen across Auckland/Waikato and the East Cape, with the remainder regions only revealing stronger negative IVT magnitudes under the 90th quantile when compared to mean conditions (Figure 4.20; Figure 4.21).

Drought during SPEI drought months over Northland, Auckland/Waikato and East Cape occurs while Southland experiences increased SPEI-3 conditions, while conversely drought over Southland and the East Coast occurs concurrently with increased SPEI-3 over the upper North Island (Figure 4.22). The deviation between the 90th quantile and mean conditions is exemplified by the longitudinal differences in SPEI-3 values, with the wet/dry contrast between the north/south of the country (Figure 4.19; Figure 4.22).

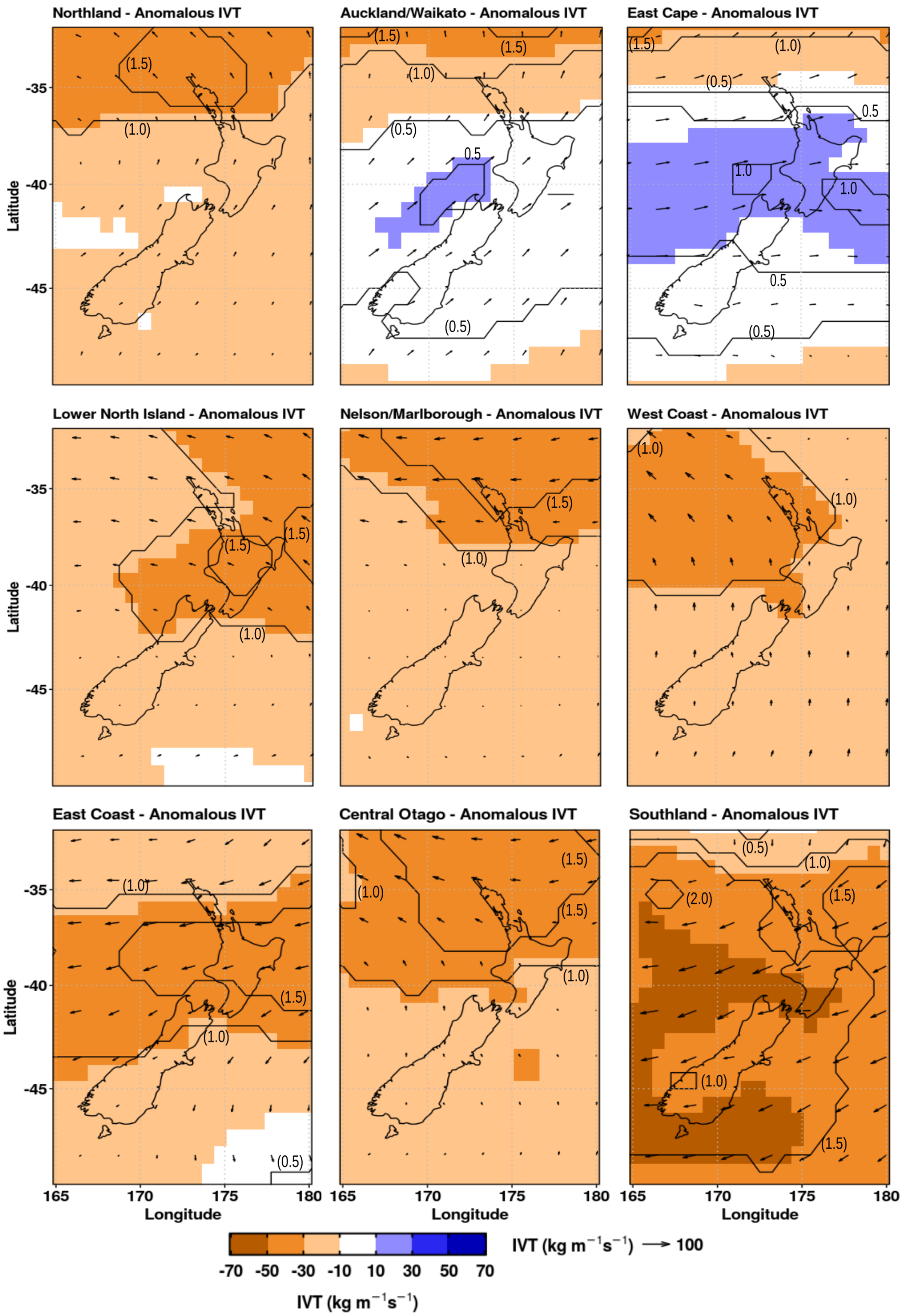

Figure 4.21: IVT anomalous conditions for the 90th quantile SPEI drought events across all regions. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction

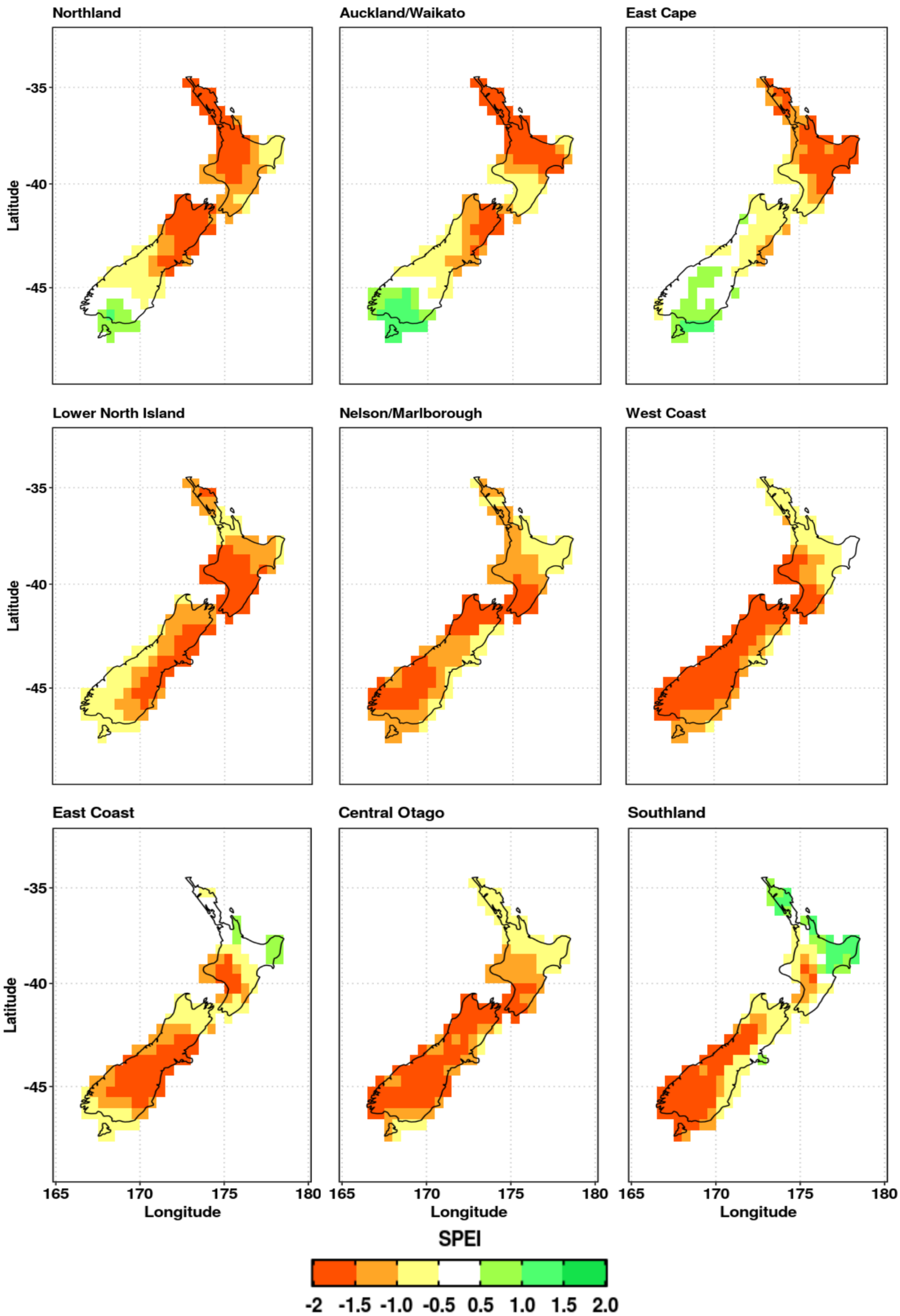

Figure 4.22: SPEI conditions during the 90th quantile of drought events across all regions for the period July 1979 to December 2010

SPEI drought months in the 90th percentile occur most frequently during autumn months across the West Coast and East Coast regions, with the East Cape also showing a common occurrence during early autumn (Figure 4.23). The 90th percentile over Southland shows a common occurrence of winter months, with late winter months also been common across the Lower North Island (Figure 4.23). For Northland, Auckland/Waikato, Nelson/Marlborough and Central Otago there is no tendency for drought to occur in any season or month in the 90th percentile, with the percentile containing a range of calendar months (Figure 4.23). The domain averaged anomalous IVT conditions in the 90th quantile are statistically significantly different to mean conditions across all regions except for Nelson/Marlborough, West Coast and Central Otago (Table 4.5).

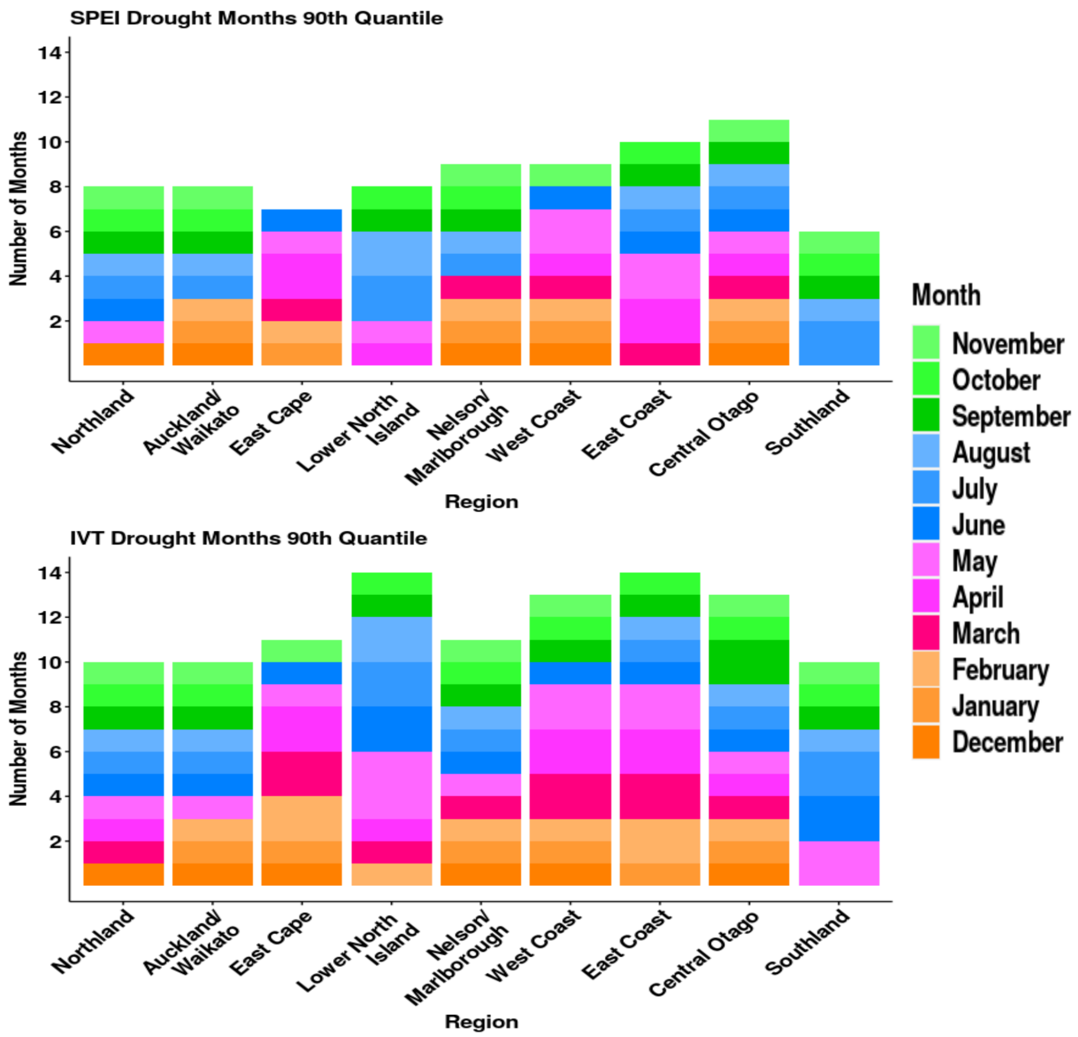

Figure 4.23: Occurrence of the 90th quantile SPEI drought months per calendar month across each region for the period July 1979 to December 2010

Table 4.5: Mann-Whitney U Test on IVT values between various categorisations of drought events and mean conditions over the same period for each region. Yellow highlighting indicates significance at the 95% level

IVT Period	Northland	Auckland/ Waikato	East Cape	Lower North Island	Nelson/ Marlborough	West Coast	East Coast	Central Otago	Southland
95th Quantile	0.03	0.00	0.03	0.62	0.31	0.93	0.00	0.89	0.00
90th Quantile	0.03	0.00	0.03	0.00	0.49	0.07	0.01	0.34	0.00
80th Quantile	0.34	0.00	0.03	0.22	0.70	0.00	0.36	0.34	0.00
January	0.03	0.00	0.03	0.02	0.49	0.00	0.02	0.34	0.01
February	0.03	1.00	0.03	0.00	0.59	0.00	0.00	0.34	0.38
March	0.34	0.00	0.03	0.29	0.02	0.00	0.00	0.34	0.17
April	0.03	0.00	0.69	0.00	0.01	0.00	0.44	0.34	0.01
May	0.03	0.00	0.03	0.01	0.13	0.09	0.04	0.34	0.03
June	0.03	0.34	0.03	0.05	0.31	0.00	0.07	0.49	0.40
July	0.03	0.00	0.03	0.00	0.03	0.13	0.02	0.34	0.04
August	0.03	0.00	0.11	0.00	0.59	0.01	0.00	0.34	0.01
September	0.03	0.26	0.03	0.04	0.39	0.00	0.04	1.00	0.00
October	0.20	0.00	0.03	0.51	0.59	0.00	0.00	0.34	0.04
November	1.00	0.00	0.03	0.00	0.94	0.01	0.01	1.00	0.03
December	0.49	0.00	0.06	0.06	0.31	0.00	0.00	0.34	0.16

4.5.5.2 Monthly Analysis of Regional SPEI

Due to length constraints, only a small number of representative months were examined for each region, in contrast to all months for the national analysis. January was selected as representative of summer drought conditions, with July being selected as representative of winter drought conditions. These seasons were chosen for further investigation due to the disparity in droughts between the two seasons seen New Zealand wide (Figure 4.10; Section 4.4.3.2). January and July were specifically selected as a visual examination revealed them to be representative of the mean seasonal conditions across the majority of regions. Section 3.6 discusses this in further detail. Composites of all SPEI drought months in January and July were taken, alongside composites of IVT conditions during IVT drought months during January and July.

January drought conditions highlight a contrast between the islands of New Zealand, with declines in both moisture and the westerly flow of moisture witnessed across the South Island regions (Figure 4.24). Except for the East Coast and Central Otago, these declines in the westerly flow of moisture are particularly strong (Figure 4.24). Over the North Island, all regions experience increases in the westerly flow of moisture and the moisture flux itself, with only the Lower North Island region showing small signs of changes in flow direction and moisture flux occurring to the upper north of the island (Figure 4.24).

In contrast to the changing conditions on a regional level in January droughts, July drought events reveal a more uniform pattern of IVT conditions across all regions (Figure 4.25). Across most regions a decline in the westerly flow of moisture is present, with the strength of this decline decreasing the further south down the country each region is (Figure 4.25). Associated with the westerly decline are declines in the moisture flux across the affected regions (Figure 4.25). Changes in IVT during all IVT drought months for January and July are statistically significantly different to mean IVT conditions for the same months across all regions, except Nelson/Marlborough (January), West Coast (July) and Central Otago (January and July) (Table 4.5).

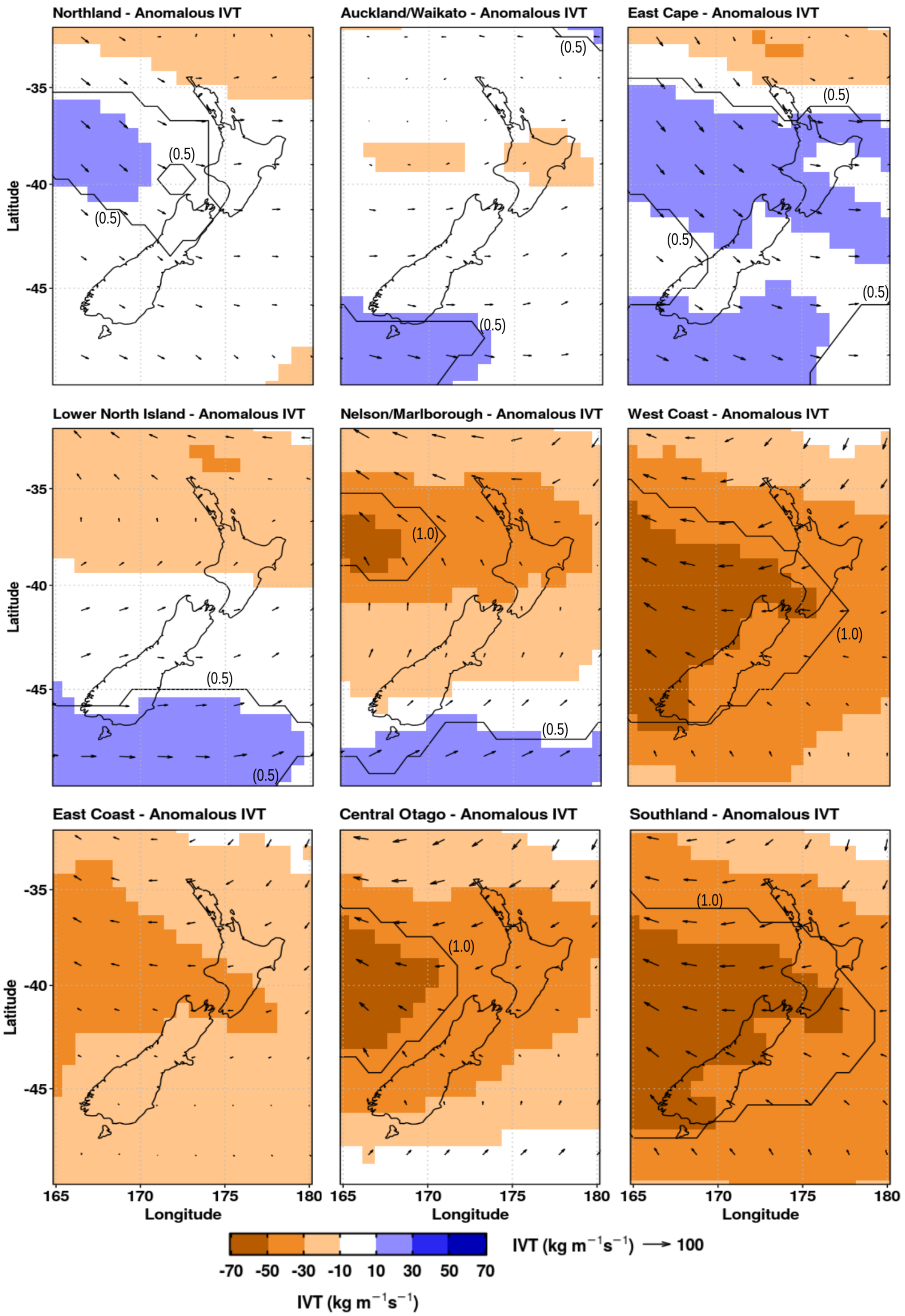

Figure 4.24: IVT anomalous conditions for all regions for the month of January. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction

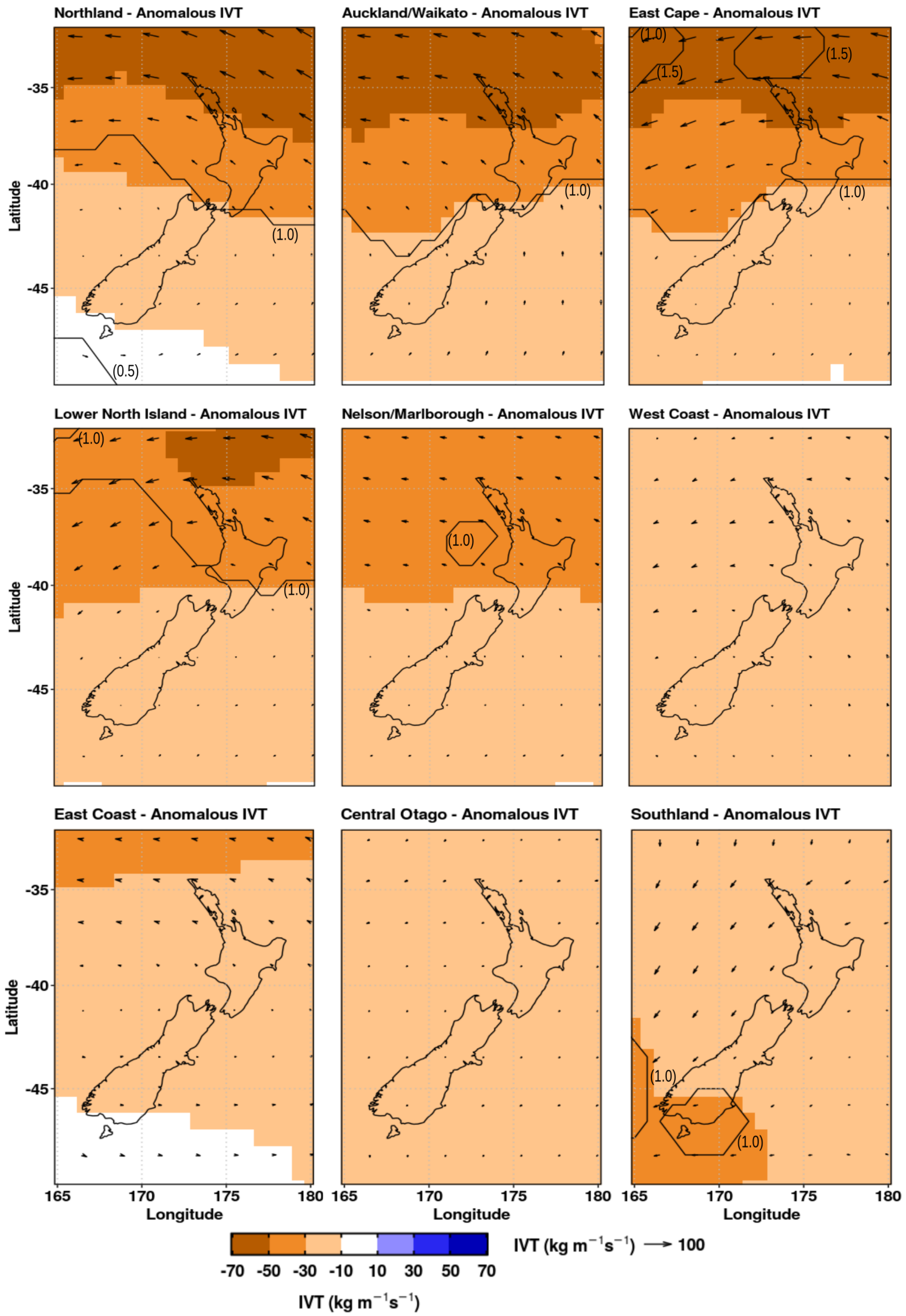

Figure 4.25: IVT anomalous conditions for all regions for the month of July. Contour lines and labels indicate the number of standard deviations IVT anomalies are from the mean, in either a positive or negative direction

January droughts across the regions show greater variation in SPEI-3 conditions across the country (Figure 4.26). Droughts over Northland, Auckland/Waikato and East Cape occur concurrently with neutral to positive SPEI-3 conditions across much of the South Island, while droughts across the West Coast, East Coast and Southland occur concurrently with neutral or positive SPEI-3 conditions across much of the North Island (Figure 4.26). In contrast, droughts during July show a greater spatial distribution of negative SPEI-3 conditions across the country under each regional drought (Figure 4.27). Neutral SPEI-3 conditions are seen over the West Coast during Northland droughts, while conversely East Cape shows neutral conditions during West Coast droughts (Figure 4.27). All other regional droughts during July reveal negative SPEI-3 conditions across the entire country (Figure 4.27).

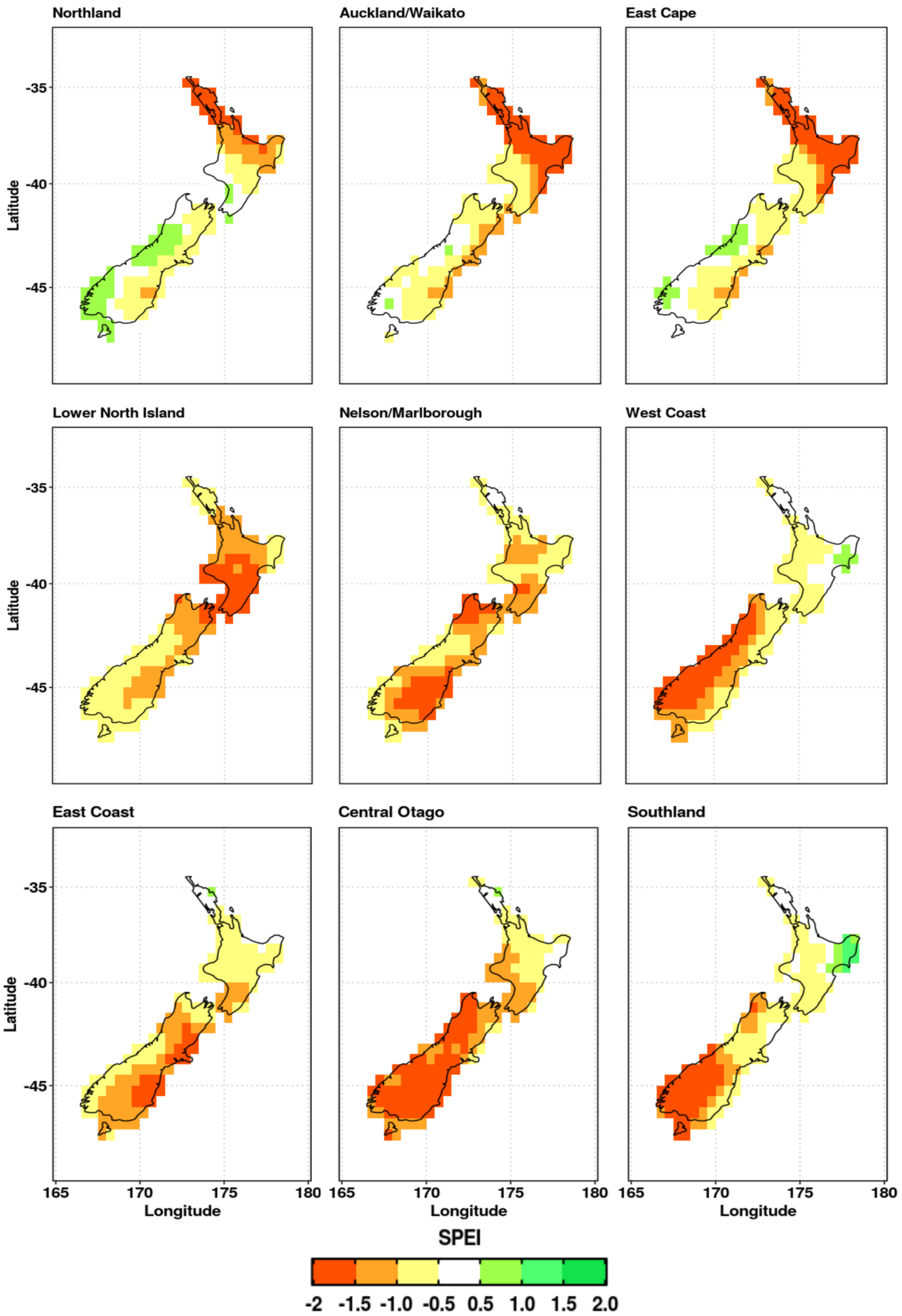

Figure 4.26: SPEI-3 conditions during January drought events across all regions for the period July 1979 to December 2010

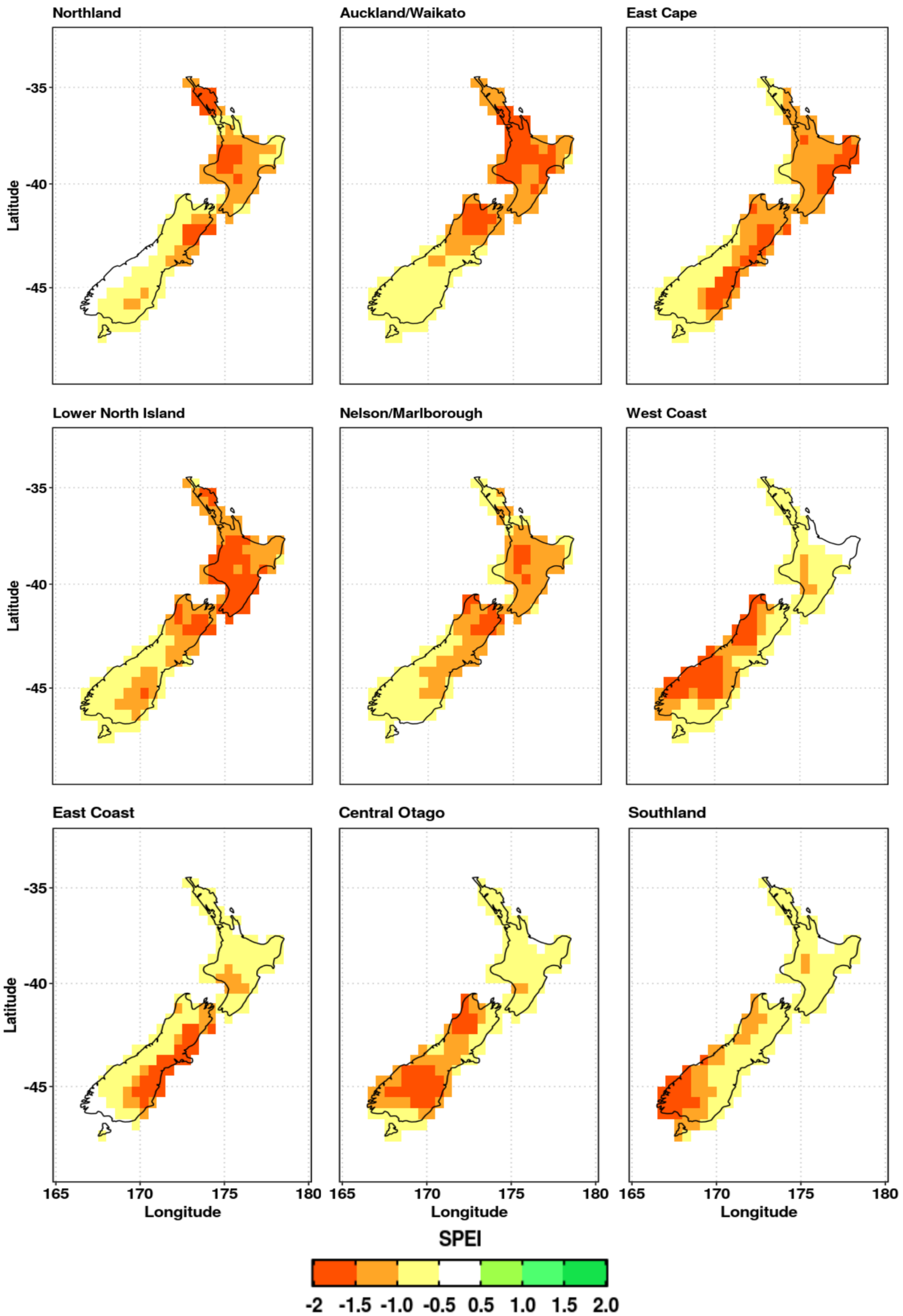

Figure 4.27: SPEI-3 conditions during July drought events across all regions for the period July 1979 to December 2010

4.5.6 Regional Analysis: Climate to Environment

The identification of the SOM nodal scheme was performed in Section 3.5.4, which classified IVT fields for each month from July 1979 to December 2010 into one of the 25 nodes. Averages were then taken of anomalous IVT conditions and SPEI-3 conditions during each node. The final output was a single map of 25 nodes which represented a classification of IVT patterns for the New Zealand study domain (Section 3.5.4). The following analysis on a regional level was performed by investigating the association of each node with drought events for each region (i.e. no new nodal maps were produced). This enables identification of important nodes to each region, while still enabling comparisons between regions. Similar to previous comments in Section 4.5.5, due to length constraints only the 90th quantile, January (summer) and July (winter) are discussed.

4.5.6.1 Analysis of 90th Quantile SPEI Drought Events

First, SPEI drought months during the 90th quantile are investigated for their frequency of occurrence amongst the 25 nodal pattern scheme. SPEI drought months within the 90th quantile occur across a range of nodes within all regions, with a dominance of node 2 and 11 across the East Coast and Southland regions being the largest single grouping of SPEI drought months (Figure 4.28). Node 2 occurs across the East Coast under four SPEI drought months, while node 11 also occurs across Southland during four SPEI drought months (Figure 4.28). Other notable groupings include nodes 11 and 25 across Northland, Auckland/Waikato and the East Cape, with nodes 11/25 characterised by strong decreases/increases in westerly moisture flow and magnitude across the entire country (Figure 4.11). Associated with nodes 11 and 25, SPEI drought months occur in Northland (2 and 2 SPEI drought months respectively), Auckland/Waikato (2 and 3) and East Cape (0 and 3) (Figure 4.28). Nodes 2 and 14 also feature during SPEI drought months over the Lower North Island (2 and 2) (Figure 4.28). Finally, nodes 16 and 17 occur across the West Coast (2 and 2) and Central Otago (2 and 1) during SPEI drought months (Figure 4.28).

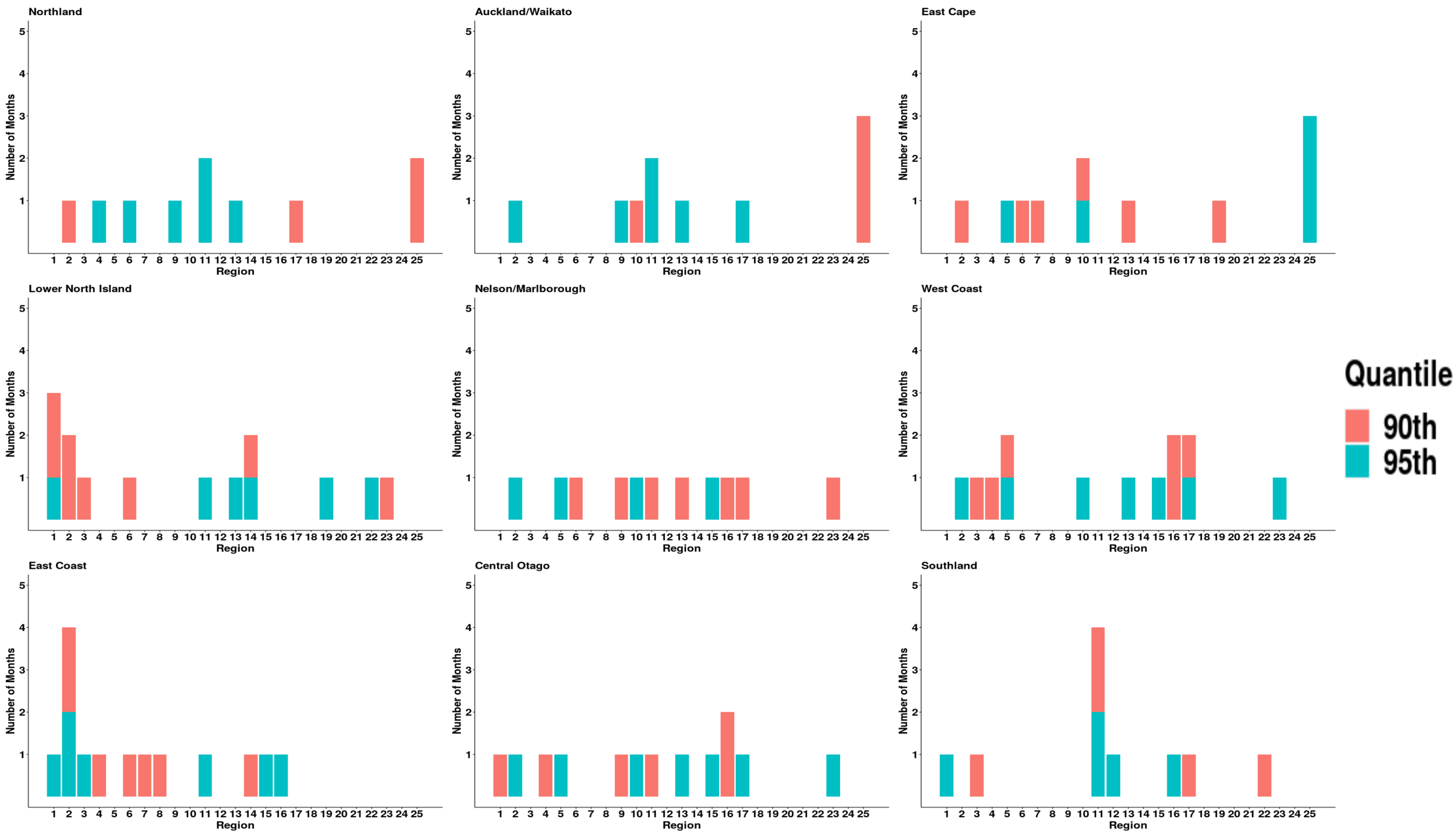

Figure 4.28: Frequency of SOM nodes during top quantiles of SPEI drought months across all regions for the period July 1979 to December 2010

4.5.6.2 Analysis of January (Summer) Events

Next, January SPEI drought months are investigated alongside their occurrence during each of the 25 nodes. No dominance of nodes occurred across any SPEI drought months across any region, although regional tendency towards particularly nodes is present. January SPEI drought events show a regional tendency towards occurring during nodes 4, 5, 15 and 25 across Northland (1,0,1,1 SPEI drought months respectively), Auckland/Waikato (1 each) and East Cape (1,1,2,1), while nodes 4 and 5 also contain January SPEI drought months across the Lower North Island (1 and 2) (Figure 4.29). Nodes 3, 4 and 5 feature as January SPEI drought carrying months across Nelson/Marlborough (1,1,2), East Coast (1,1,2) and Central Otago (1,1,1), with node 3 also featuring across Southland (1) and the West Coast (1) (Figure 4.29). Node 13 over both Northland (1) and the West Coast (1) contains January SPEI drought months, while nodes 10 and 15 are present during January SPEI drought months for the Lower North Island (1,1), Nelson/Marlborough (1,0), West Coast (1,0) and Central Otago (1,0) regions (Figure 4.29). In comparison with the nationwide analysis of SPEI drought months associated with nodes (Figure 4.13), nodes 13 and 25 do not feature in the nationwide analysis during summer periods. These nodes tend to occur during regional January drought events across Northland (node 13 and 25), Auckland/Waikato (node 25), East Cape (node 25) and West Coast (node 13) (Figure 4.29).

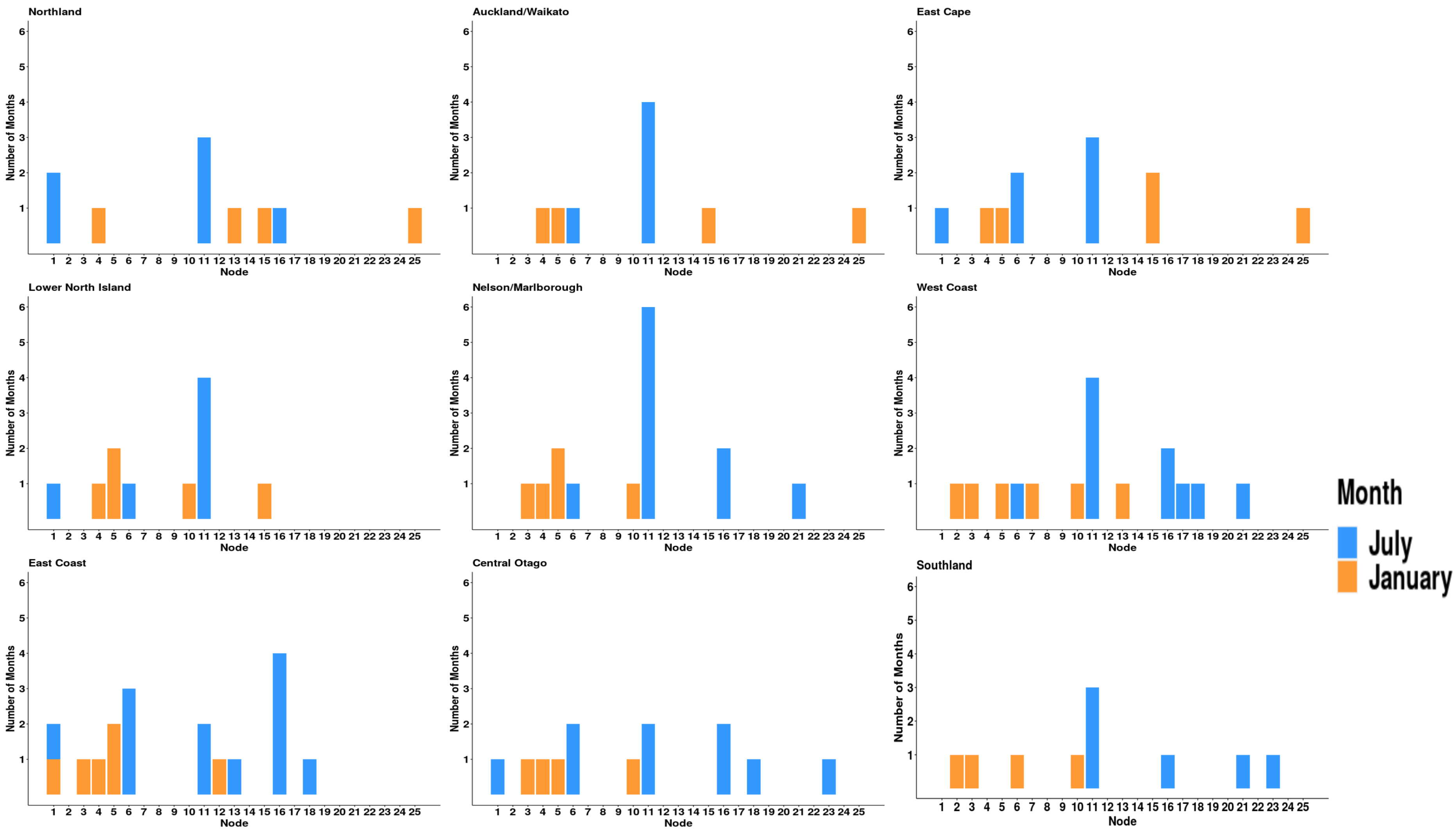

Figure 4.29: Frequency of SOM nodes during SPEI drought months across all regions for the period July 1979 to December 2010

4.5.6.3 Analysis of July (Winter) Events

Following the January analysis, the same process was repeated for July SPEI drought months. In contrast to the large variation in classification of January SPEI drought months, July drought months offer a more uniform classification across the regions. July SPEI drought months share common nodal occurrences across all regions, largely under nodes 6, 11 and 16 (Figure 4.29). Node 11 is the dominant node across Northland (3 SPEI drought months), Auckland/Waikato (4), East Cape (3), Lower North Island (4), Nelson/Marlborough (6), West Coast (4) and Southland (3) (Figure 4.29). It also features across East Coast (2) and Central Otago (2) but is not the dominant node (Figure 4.29). Node 6 and 16 are dominant across Central Otago (2 and 2 SPEI drought months respectively), while also featuring across Northland (0 and 1), Auckland/Waikato (1 and 0), East Cape (2 and 0), Lower North Island (1 and 0), Nelson/Marlborough (1 and 2), West Coast (1 and 2) and Southland (0 and 1) (Figure 4.29). Both nodes also feature heavily across the East Coast, with node 16 being the dominant node (3 and 4 SPEI drought months). In comparison with the nationwide analysis of SPEI drought months associated with nodes (Figure 4.13), all nodes share a similar pattern to that revealed on the regional analysis, with a strong tendency towards nodes 6, 11 and 16 revealed during the nationwide analysis.

4.5.7 Regional Drought Events Summary

Peaks in drought coverage are seen during the 1980s across North Island regions, as well as peaks in the late 1990s/early 2000s across the entire country except Northland. Top quantile drought events across the upper north regions occur concurrently with neutral or positive SPEI-3 values across the bottom of the country and vice versa. Regions across the middle of the country reveal negative SPEI-3 values across the entire country during top quantile drought events. IVT across the top quantiles reveals a decline in northerly moisture flow and moisture flux over Northland and Auckland/Waikato, an increase in westerly moisture flow and moisture flux over East Cape, and minor strengthening northerly moisture flow (East Coast) and decrease northerly moisture flow (Central Otago) associated with decreased moisture flux across both regions. Winter and spring remain the most dominant periods across all regions, while summer periods feature the greatest changes in moisture flux and direction. Winter periods are characterised by minor declines in moisture flux and westerly moisture flow across all regions, while summer periods are characterised by a north/south dipole, with North Island regions featuring increased westerly moisture flow and IVT magnitude, while South Island regions feature decreased IVT westerly flow and magnitude. The same dominance of nodes witnessed across New Zealand is similarly noted across regions, with the noted addition of node 25 for the East Cape which does not feature in the New Zealand wide analysis.

4.6. Summary

The time series of SPEI-3 follows closely to that of the other accumulation periods, with greater increases and decreases in drought coverage witnessed as the accumulation periods increases. IVT across the New Zealand region shows a pattern of minor decreases in the westerly moisture flow and flux to the south of New Zealand during winter, with an increased moisture flow and flux over summer. Top quantile events occur during later winter and early spring, while regionally there is an opposing relationship of drought events in the upper north regions occurring concurrently with neutral or positive SPEI-3 values over the south, and vice versa. IVT during these periods shows decreased magnitude and westerly movement over the North Island, with weaker declines in both over the South Island.

The summer period reveals the strongest changes in IVT across regions, with the South Island featuring more even declines in IVT magnitude and westerly flow, while the North Island highlights increased directional flow and magnitude across the island. Northland and Auckland/Waikato experience declines from the north, while East Cape experiences increase in westerly moisture flow and magnitude. The nodal map reveals commonalities with the composite maps produced, with the frequent occurrence of increased westerly moisture flow across East Cape under node 25, decreased northerly moisture flow over Northland and Auckland/Waikato under node 6 and decreased westerly moisture flow and IVT magnitude under nodes 6 and 11 across Central Otago and East Coast.

5. Discussion

5.1. Introduction

The following chapter will analyse the performance of the SPEI alongside the relationship between SPEI-3 and IVT across New Zealand and regions over New Zealand. Firstly the performance of the SPEI-3 is evaluated with the other accumulation periods that were available from the dataset (Section 5.2.2), before investigating the performance of the clustering of SPEI-3 in regional identification amongst existing research (Section 5.2.3). Comparisons are also made to existing research on drought events over New Zealand (Section 5.2.4). The relationship between SPEI-3 and IVT is then evaluated, both over New Zealand and on a regional basis using composite maps (Section 5.3). Unique regional characteristics are identified and discussed with existing research on drought development. Countrywide and regional characteristics are then analysed using the SOM method, where the performance of the method is reviewed in conjunction with other weather typing tools, as well as against the composite maps provided earlier (Section 5.4). Similarities and contrasts between the two methods are discussed. A synthesis is then provided which pulls together the results from both the environment to climate and climate to environment methods (Section 5.5).

5.2. Temporal and Spatial Variability of SPEI

5.2.1 Introduction

The following section will focus solely on an analysis of the SPEI-3 dataset used in the current study. First, the performance of the SPEI-3 will be analysed with the other accumulation periods provided in the study: SPEI-1, SPEI-6, SPEI-12 and SPEI-24. Next, the focus will shift to a closer investigation of the SPEI-3 by evaluating how the spatial characteristics of the index are expressed over New Zealand. This is done by analysing the cluster of regions in the current study to existing research which has used various other clustering techniques. As part of this, the regional expression of SPEI-3 values will also be inspected. Finally, analysis of the SPEI-3 will be performed from a temporal perspective, by investigating how the SPEI-3 characterises previously studied drought events. Possible explanations as to differences in performance will also be introduced.

5.2.2 Accumulation Periods

Changes in the temporal resolution of the accumulation periods is a commonly noted feature in the SPEI's approach to drought quantification, with Vicente-Serrano *et al.* (2014) noting that the various response times between climate signals and drought can be represented and simulated using these different temporal resolutions. Moving from one month accumulation periods through to 24 month accumulation periods mimics this finding from Vicente-Serrano *et al.* (2014), with the higher accumulation periods representing the accumulated response of the hydrological regime over longer time periods. For example, the 24 month accumulation period provides a more capable proxy of antecedent conditions which could be associated with soil moisture and groundwater conditions, resulting in greater drought coverage across the country throughout the mid 1990s to mid 2000s (Figure 4.2). This period of New Zealand wide dry conditions from the mid 1990s to the mid 2000s was similarly identified by Kingston and Treadwell (in press) using the SPI and SPEI on six month accumulation periods, with the period 2000/2001 identified by Salinger and Porteous (2014) using Accumulated Potential Evapotranspiration Deficit (PED) as a particularly severe period of drought across New Zealand. The increased drought coverage and more negative SPEI values in the 24 month accumulation period are the result of the slow response rate to changes in precipitation and temperature, as well as the long memory once a response has occurred, giving the 24 month accumulation period a smoother curve under Figure 4.2. These findings mimic those of previous research by McKee *et al.* (1993) and Manning *et al.* (2018) on the general performance of both the SPI and SPEI when used in conjunction with long accumulation periods across a number of locations.

Conversely, the one month accumulation period reveals less strongly negative SPEI values compared to the 24 month period (Figure 4.1), suggesting a quicker response to changes in climatic conditions as precipitation and evapotranspiration are not attenuated in the smaller accumulation period. The lack of attenuation is also indicative of the lack of recognition of antecedent conditions throughout the country. This is further evidenced by the quick responses to changes in drought coverage across the country, with larger variation and less smoothing seen across the time series (Figure 4.2), similar to existing research by Lorenzo-Lacruz *et al.* (2010) and Vicente-Serrano and López-Moreno (2005). The one month accumulation period does identify more drought events than that evidenced by Kingston and Treadwell (in press) using the SPEI-6 and by Caloiero (2017) using the SPI-3. The one month accumulation period shows an earlier onset of drought conditions in comparison to the SPEI-3 and SPEI-6 (Figure 4.2), a symptom of its relatively strong coupling to recent precipitation changes (Manning *et al.*, 2018). It also reveals an earlier cessation of drought (Figure 4.2), further highlighting its poor performance in accounting for slow moving hydrological processes which are better represented by longer accumulation periods (López-Moreno *et al.*, 2013). With many groundwater driven catchments across New Zealand, such as those of the Canterbury and East Cape regions (White, 2001), the smaller accumulation periods are unlikely to capture these processes well.

The three month accumulation period responds similarly to that of the one month accumulation period: a relatively quick response time to changes in climatic conditions, exemplified by the fluctuation in mean SPEI-3 and changes in drought coverage over New Zealand across the time period (Figure 4.2). For example, drought coverage is approximately 40% higher under the SPEI-24 than the SPEI-3 across the 2001 period (Figure 4.2). The identification of late winter/early spring as a prominent season for strong drought events (Figure 4.7) highlights the SPEI-3's function at identifying clear seasonal variability in precipitation and evapotranspiration, with the longer accumulation periods attenuating these seasonal variations, making the identification less concise.

While the SPEI-3 does identify drought events previously mentioned in multiple studies by Caloiero (2017), Kidd (2015) and Kingston and Treadwell (in press) amongst others, these drought events appear to be of lesser magnitude both spatially and temporally to these previous studies. These differences are discussed further in Section 5.2.4, with an early example being the 18 consecutive months in drought between 1982 and 1984 in the work of Caloiero (2017), compared with the five months across three separate events in the present study over the same period (Table 4.1). These differences could be attributed to different methodologies and threshold values, meaning that comparisons between drought studies across New Zealand should be treated with caution. This again illustrates the difficulty in drought research: the lack of consistent application of drought definition and methodology means that comparing indices is difficult (Mishra and Singh, 2010), although such research can reveal important information on the functionality of different indexes and the appropriate choice of drought threshold. With existing research highlighting that longer accumulation periods may be better able to track hydrological droughts (López-Moreno *et al.*, 2013; Lorenzo-Lacruz *et al.*, 2010; Vicente-Serrano and López-Moreno, 2005), the findings of similar time series changes in the SPEI-3 to longer accumulation periods suggest a utility in the use of the SPEI-3 to monitor hydrological drought. The fluctuations in the SPEI-3 time series illustrates an ability to detect seasonal variation as an outcome of the shorter accumulation periods (Figure 4.2), which as noted by Szalai *et al.* (2000) allows for greater assessment of hydrological process within a catchment, such as snowmelt. With the attenuating effect of longer accumulation periods, such changes do not immediately respond within the SPEI, thus seasonal variation can become less clear in longer accumulation periods.

As one of the goals of this research was to examine the role of hydrological drought across New Zealand, it must be reinforced at this point that the user of this information does not overstate its relevance to other forms of drought, such as agriculture or meteorological drought. Previous research across New Zealand using SPEI-6 (Kidd, 2015; Kingston and Treadwell, in press) revealed meteorological drought occurrence that closely matches with the current research using SPEI-3 (Figure 4.2; Table 4.1), suggesting it is capable of similar performance when monitoring meteorological drought. The use of SPI-2 in the NZDI was chosen by Mol *et al.* (2017) to monitor meteorological and agricultural drought, as a period of two months of well below normal rainfall was shown to be sufficient to trigger drought like conditions, although Mol *et al.* (2017) did not expand on the specifics of what these drought like conditions may look like. The use of SPI-2 by Mol *et al.* (2017)

supports the use of the SPEI-3 in tracking precipitation deficits that trigger drought, with both methods being of similar time steps, which together with the comparison to Kingston and Treadwell (in press) further supports the use of the method and accumulation period in tracking meteorological and agricultural drought. However, its performance in tracking hydrological drought remains to be directly tested across New Zealand.

5.2.3 Spatial Variability in SPEI

5.2.3.1 Nine Region Identification

The identification of nine regions in the cluster analysis of SPEI-3 follows a similar theme to those regions identified by Kingston and Treadwell (in press), with the difference of the Northland, Auckland/Waikato and East Cape regions being represented by a single region in the research of Kingston and Treadwell (in press). Mean drought conditions across the entire country reveal strongly negative SPEI-3 values across much of the country, with the exclusion of the Northland, Auckland/Waikato and East Cape regions (Figure 4.5). The more neutral SPEI-3 values across these regions are reflected in the number of months during drought conditions across the country, with all three regions showing the least number of months in drought apart from Southland (Figure 4.18).

Because the same datasets were used between the analysis in the current research and that of Kingston and Treadwell (in press), the differences between the research on the six region level highlights the changing characteristics of the regions under SPEI-3 in comparison to the SPEI-6 used by Kingston and Treadwell (in press). Regionally, the six regions identified using SPEI-3 closely match those of the SPI on a 6 month accumulation period (SPI-6) in Kingston and Treadwell (in press) (Figure 4.15). Similarly, the SPEI-6 clusters identified by Kingston and Treadwell (in press) also align with the SPEI-3, although greater differences are visible. The closer association between SPI-6 and SPEI-3 allows for a greater assessment of how smaller accumulation periods of PET respond across the regions.

The similarity between the six region SPI-6 in Kingston and Treadwell (in press) and the six region SPEI-3 highlights the theme of lower accumulation periods being more apt at tracking immediate changes in climatic variables than under the longer accumulation periods (Manning *et al.*, 2018). The SPEI-3 appears to be tracking precipitation changes in much the same manner as the SPI-6 does, with PET having less of an influence on SPEI-3 conditions, highlighting its importance as a second order driver of drought and the presence of an extended memory to PET values (Manning *et al.*, 2018). Kingston and Treadwell (in press) suggested that the diverging trend over some regions of New Zealand between SPI and SPEI may be further exaggerated under shorter accumulation periods as a result of a closer connection to the typical meteorological drought timescale. While SPI was not examined in the present study, the results can be compared to the work of Caloiero (2017) where the SPI was used over a 3 month accumulation period. The Caloiero (2017) SPI shows a similar percentage of the country under drought as a whole, suggesting that the diverging trend between SPI and SPEI proposed by Kingston and Treadwell (in press) is not increased under the shorter accumulation period (Figure 4.2). The broad nationwide spatial scale of Caloiero (2017) does not allow the separate identification of regions where a diverging trend may be seen, thus the proposal by Kingston and Treadwell (in press) should not be discounted.

The identification of East Cape as a separate region under the SPEI-3 suggests that for the East Cape region the small accumulation period of the SPEI-3 is unable to capture PET conditions, as regional identification under the SPEI-6 of Kingston and Treadwell (in press) encompassed the Auckland/Waikato region. Further, the spatial expression for East Cape is the same as that of the SPI-6 by Kingston and Treadwell (in press), suggesting that PET conditions are not accurately captured under the SPEI-3. The inclusion of PET with the SPEI-6 results in the East Cape region merging with the surrounding upper north in the cluster analysis of Kingston and Treadwell (in press), illustrating an ameliorating effect of PET on drought over the East Cape which is not captured using the SPEI-3. This ameliorating effect is the outcome of low PET rates during periods of low precipitation (Kingston and Treadwell, in press). Having identified that PET changes are poor at capturing the persistence of drought conditions on smaller accumulation levels (Manning *et al.*, 2018), PET is less influential under the SPEI-3 than the SPEI-6 as the smaller accumulation period cannot capture the long term changes in PET. Thus the East Cape remains dominated by the more variable precipitation under the SPEI-3 and leads to its separate identification amongst the cluster analysis in the current research (Figure 4.15). This finding is supported in the analysis by Kingston and Treadwell (in press) on the difference over East Cape between SPI-6 and SPEI-6, where separate regional identification of East Cape under SPI-6 is attributed to the influence of PET on the SPEI-6 which merges the region with Auckland/Waikato. Collectively, the results indicate the importance of PET during drought events across the East Cape region, similarly noted by Kingston and Treadwell (in press).

While the findings of Vicente-Serrano and López-Moreno (2005) support the use of smaller accumulation periods with standardised indices to represent hydrological drought, their study was conducted using just the SPI in a highly localised setting. The work of López-Moreno *et al.* (2013) also supports the use of small accumulation periods using the SPEI, by investigating the correlation of various SPEI accumulation periods to the Standardised Streamflow Index (SSI). Strong correlations between SPEI on two-four month accumulation periods and the SSI were shown with rivers in unregulated headwater regions across the Ebro basin. Those sub basins with a heavy groundwater influence, or where anthropogenic influence such as dam building has occurred, showed a higher correlation between SPEI and the SSI on longer accumulation periods (6-20 months) (López-Moreno *et al.*, 2013). With the East Cape region dominated by shallow, unconfined aquifers which supplement low summer flows (Gordon, 2001), the groundwater influence across the region does suggest the use of smaller SPEI accumulation periods may be unable to capture the regulating effects of groundwater storage, leading to an overestimation of drought magnitude and frequency.

5.2.3.2 Other Regional Classifications

The regional identification of Salinger and Porteous (2014) using Rotated Principal Component analysis (RPC) shows close agreement with the current regions (Figure 4.15). It should be noted that the differences may be attributed to the use of different data sources (PED station data vs. gridded SPEI-3 data), while the differing accumulation periods (12 months by Salinger and Porteous (2014), 3 months in the current research) should not be forgotten and may explain variation between identified regions. Salinger and Mullan (1999) similarly identified several regions of similar temperature and precipitation time series variability which loosely identify with the nine regions of the current study, as do the regions identified by Mojžíšek (2005) over the South Island. Differences in data sources and methodology may be the cause of differences in regional identification, with Mojžíšek (2005) using station data and RPC analysis in comparison to the clustering methodology and gridded climate data used in the current study (Chapter 3). A greater number of stations were used in the Mojžíšek (2005) study, compared to those contributing to the WFD and WFDEI datasets (Section 3.4.1). However, the ability of the regions identified by Mojžíšek (2005) to closely follow those of the current research highlights the importance and dominance of precipitation to the identification of drought, further highlighting PET as a second order factor in the calculation of drought conditions over the South Island.

Further regional identification was performed by Singh *et al.* (2017), who manually identified six regions as being representative of the complex climate across New Zealand. These regions were adapted from the New Zealand Meteorological Service climatic map series, and again roughly align with the cluster analysis performed in the current study (Figure 4.15). Noticeable differences include the separation of Auckland/Waikato and Northland into two distinct regions in the present study (Figure 4.15) but not identified by Singh *et al.* (2017), and the identification of Napier/Hastings in the work of Singh *et al.* (2017) as a separate region. Descriptive comments in Singh *et al.* (2017) do suggest the Napier/Hastings region is similar to that of the East Cape region (Chappell, 2016) in the current study (Figure 4.15). The inclusion of Napier/Hastings in the Lower North Island region in the current study is again a likely result of the station based identification used by the Meteorological Service climate series compared with the gridded data sets in the current study and the different data types used, with the complex climate of New Zealand unable to be a captured at such a fine resolution using gridded climatic data (Ackerley *et al.*, 2012). With Singh *et al.* (2017) selecting weather stations as representative of manually determined climate zones of New Zealand, these differences may simply be a result of the increased clustering regions selected in the current study. The close agreement with numerous existing literature does suggest that the nine region clusters are representative of the general climatic differences across New Zealand.

5.2.4 Temporal Variability in SPEI

5.2.4.1 Drought Events Identified by the SPEI-3

Many drought events, such as those noted by Fitzharris (1992) and Fowler and Adams (2004) are identified by the SPEI-3. The hydro-electrical crisis of 1992 is an example of hydrological drought, as noted by Fitzharris (1992), and is exemplified by low lake storage levels and continued drought in the catchments feeding the hydro-electrical lakes across the South Island. It was identified by Fitzharris (1992) using run-off data from various hydro storage lakes in the South Island. The winter of 1992 is ranked as the 5th strongest drought event across New Zealand in the current research (Table 4.1), with both the West Coast and Southland regions revealing spikes in drought coverage (Figure 4.17). Further, as noted by Fitzharris (1992), a drought in the preceding winter of 1991 was a contributor to the low lake levels of 1992, further exacerbating drought conditions across the winter of 1992.

This 1991 winter drought is also identified by the SPEI-3, ranked as the 7th strongest event (Table 4.1). However, the intervening period does not register drought conditions, which can be attributed to the threshold level set, or the inability of the SPEI-3 to track long hydrological droughts. Applying a uniform drought detection threshold to the entire country creates uncertainty in the assumed uniform characteristics of catchments. With individual catchments all revealing unique characteristics relating to topography, geology, climate and soil type, applying such a uniform methodology is unlikely to accurately capture the hydrological regime for all regions equally (Van Loon, 2015).

An illustration of the SPEI-3's inability to track the Fitzharris (1992) drought is visible in Figure 5.1, where SPEI-6 across the period identified by Fitzharris (1992) shows closer agreement to the conditions noted by Fitzharris (1992). While the SPEI-3 identifies both periods of drought in 1991 and 1992 noted by Fitzharris (1992), it is unable to track the impact of the initial 1991 event through the hydrological system. When the 1992 event occurs, the impacts are more severe in the hydropower lakes compared to the SPEI-3 value, as terrestrial stores of water are already depleted (Fitzharris, 1992), with the SPEI-6 better able to track these paired events of 1991 and 1992 (Figure 5.1). While the smaller accumulation period using the SPEI-3 is unable to track snowmelt conditions, the longer SPEI-6 does show close agreement with the conditions noted by Fitzharris (1992), indicating a greater ability to mimic snowmelt processes across the longer accumulation period, particularly around Central Otago and the West Coast (Figure 5.1). The longer accumulation period is better able to encompass the main snow storage and melt period and thus offers a better representation of the average winter/spring conditions in this instance (Figure 5.1).

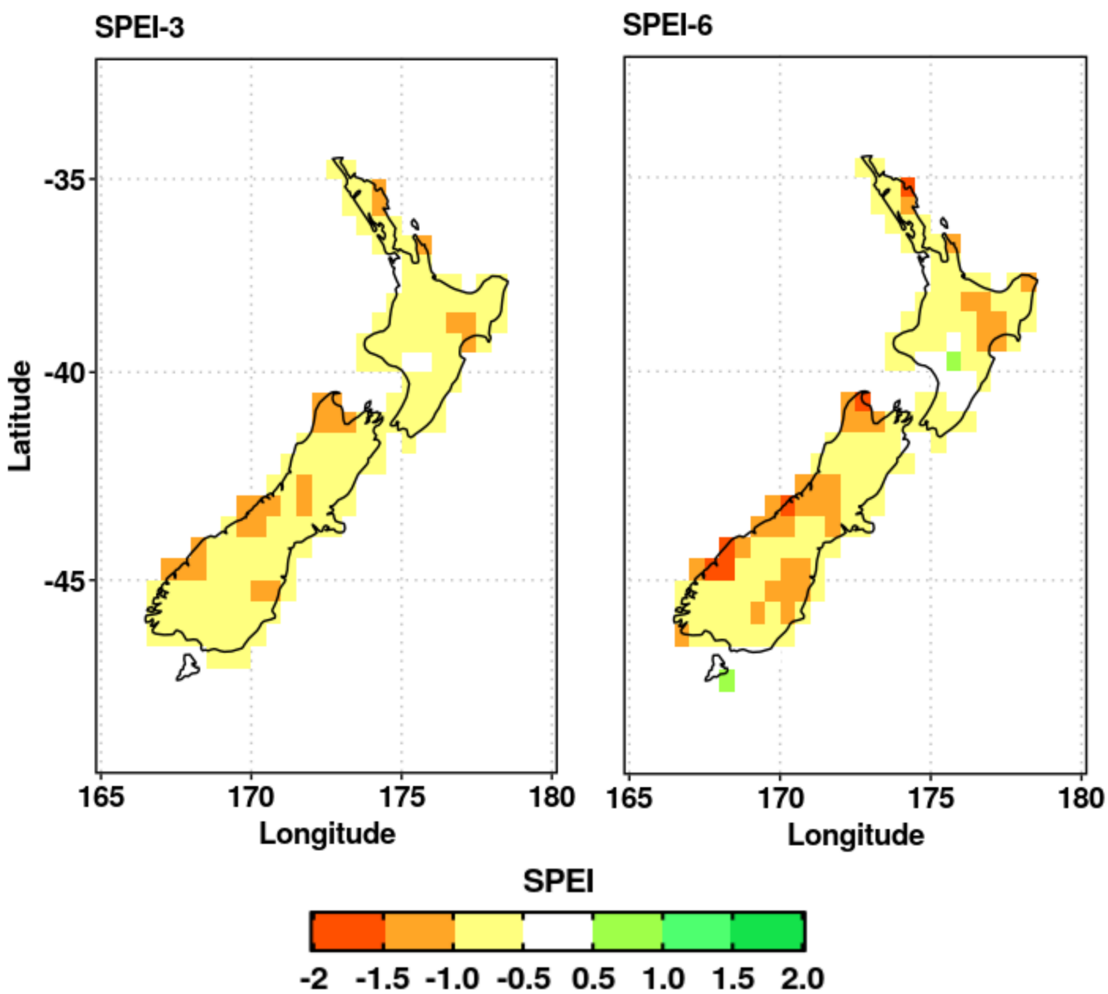

Figure 5.1: Average nationwide SPEI-3 (left) and SPEI-6 (right) for the period July 1991 to August 1992, representing a period of drought identified by Fitzharris (1992)

The drought events resulting in water crises over Auckland in 1982/1983 and 1993/1994 (Fowler and Adams, 2004) are both identified in the SPEI-3 (Figure 4.2; Table 4.1). The 1982/1983 drought was identified by Fowler and Adams (2004) based on modelling soil water, and begins in the early summer of 1982, before a recovery at the end of winter 1983, with declining reservoir levels throughout. Using the SPEI-3 in the present study, drought detection was triggered in April 1982 and continued throughout autumn (Table 4.1), with increasingly negative SPEI-3 values seen across 1982-1983 throughout Auckland/Waikato (Figure 4.16). The early detection of drought conditions during autumn by the SPEI-3 signals the start of declining reservoir levels in the present study. These conditions do not register in the study of Fowler and Adams (2004) until the summer of 1982. Throughout this period, continued negative SPEI values over Auckland/Waikato are present in the current study (Figure 4.16), although these are not sufficiently low to trigger the detection of drought conditions. The non-detection is an illustration of the difficulty in setting appropriate drought detection thresholds, similarly noted by Van Loon (2015).

The major water crisis witnessed in early 1994 across Auckland was the result of declines in reservoir storage from summer 1993 through to winter 1994 (Fowler and Adams, 2004). Again, early detection is seen in SPEI-3 values, with the strongest nationwide drought seen for the period August-October 1993 (Table 4.1), and regionally with drought conditions over Auckland/Waikato from September to November 1993 (Figure 4.17), signalling the onset of declines in expected inputs into reservoir storage. The ability to track this early onset is a noted performance measure of the smaller accumulation periods (Manning *et al.*, 2018). Again, the intervening period between the summer of 1993 and winter of 1994 contains sustained negative SPEI-3 values across the region (Figure 4.16) which are not sufficiently low to trigger drought detection with the threshold level selected in the present study.

The continued negative SPEI values which are not sufficiently negative to trigger the drought detection threshold may be an outcome of the imposition of the nationwide threshold level of -0.8 SPEI-3 onto a regional level. This occurs across both the 1982/1983 and 1993/1994 drought events identified by Fowler and Adams (2004). Alternatively, differences in the study area may explain the non-identification of drought in the current study to Fowler and Adams (2004), with the present study encompassing the entire Auckland/Waikato region as opposed to solely Auckland by Fowler and Adams (2004). The non-identification of drought in the present study compared to Fowler and Adams (2004) may also highlight a limitation of the SPEI-3 to monitor hydrological drought in heavily anthropogenic influenced catchments, as the release and storage of water within these catchments may create residence time beyond the 3 month time step (Smakhtin, 2001).

5.2.4.2 Drought Events Not Identified by the SPEI-3

The drought of 2007/2008 was identified by Salinger and Porteous (2014) using the PED method from 41 individual data stations across New Zealand, and was ranked as the strongest drought for the period 1941-2013, with low PED seen across much of the South Island and lower North Island. The specific drivers of this 2007/2008 drought are not identified in the work of Salinger and Porteous (2014), but the current work suggests that the anomalies of precipitation and PET were persistent, but not sufficiently strong in the current work to trigger the drought detection threshold. This is illustrated by the negative SPEI-3 values seen across the middle of the country which do not trigger drought detection (Figure 4.2, Figure 4.17), with average SPEI-3 values/drought coverage between July 2007 and June 2008 of around -0.24/25% nationally and -0.36/33% over the Lower North Island region. This disconnect between the non-detection under the current study and the drought being identified as the strongest in the study of Salinger and Porteous (2014) illustrates many of the nuances that exist when investigating drought, further evidenced in comments by Mishra and Singh (2010) and Wilhite and Glantz (1985) on the difficulty of accurately identifying and quantifying drought.

Difficulty exists in identifying drought on a nationwide scale, with neutral (or negative values which do not exceed the drought threshold value) contributing to create a nationwide average drought value which does not meet the threshold. Regionally however there may be particularly strong or persistent drought conditions which are not identified in the national average. During the 2007/2008 Salinger and Porteous (2014) drought event, Figure 5.2 reveals moderately negative SPEI-3 across much of the country which aligns with the areas identified as being in drought by Salinger and Porteous (2014). The use of a single nationwide index value means that average SPEI-3 is below the detection threshold and does not result in drought detection. The accumulation period used by Salinger and Porteous (2014) is also vastly different, with a 12 month accumulated deficit compared to a three month rolling window under the SPEI. Figure 5.2 illustrates this difference, with the SPEI-12 showing the same spatial pattern as drought coverage of the SPEI-3 and Salinger and Porteous (2014), but with much stronger negative SPEI values. The 12 month window of the SPEI-12, therefore, more closely aligns with the work of Salinger and Porteous (2014), and indicates the non-identification of the drought event in the current study (using SPEI-3) is a combination of the nationwide drought threshold, coupled with methodological differences.

The use of PED versus SPEI may also contribute to the discrepancy in drought identification in the current study and Salinger and Porteous (2014), with Salinger and Porteous (2014) identifying national events via an average of the five leading modes from a PCA analysis, compared to the time series and threshold analysis in the current study. By averaging across the five leading modes, (relatively) minor modes will be excluded from the analysis, thus areas of the country which have smaller PED will be excluded and not ameliorate the national average PED value. In comparison, the current study does include these areas, as the average SPEI-3 value across the entire country includes areas in neutral or positive SPEI and thus shifts the average SPEI-3 to a more neutral value. In this way, the SPEI-3 does not operate solely as a drought index, as non areas of drought are forced into the calculation. When used in conjunction with the nationwide drought detection threshold, detection is avoided for the drought event. As a result, the identification of droughts by Salinger and Porteous (2014) likely overstates the nationwide significance when compared to the current research. Applying the PED methodology in a similar manner to Mullan *et al.* (2005) would help identify the comparative significance of the two methods, as the Mullan *et al.* (2005) methodology includes all areas of New Zealand using the Virtual Climate Station Network (VCSN), thus revealing a more representative nationwide average.

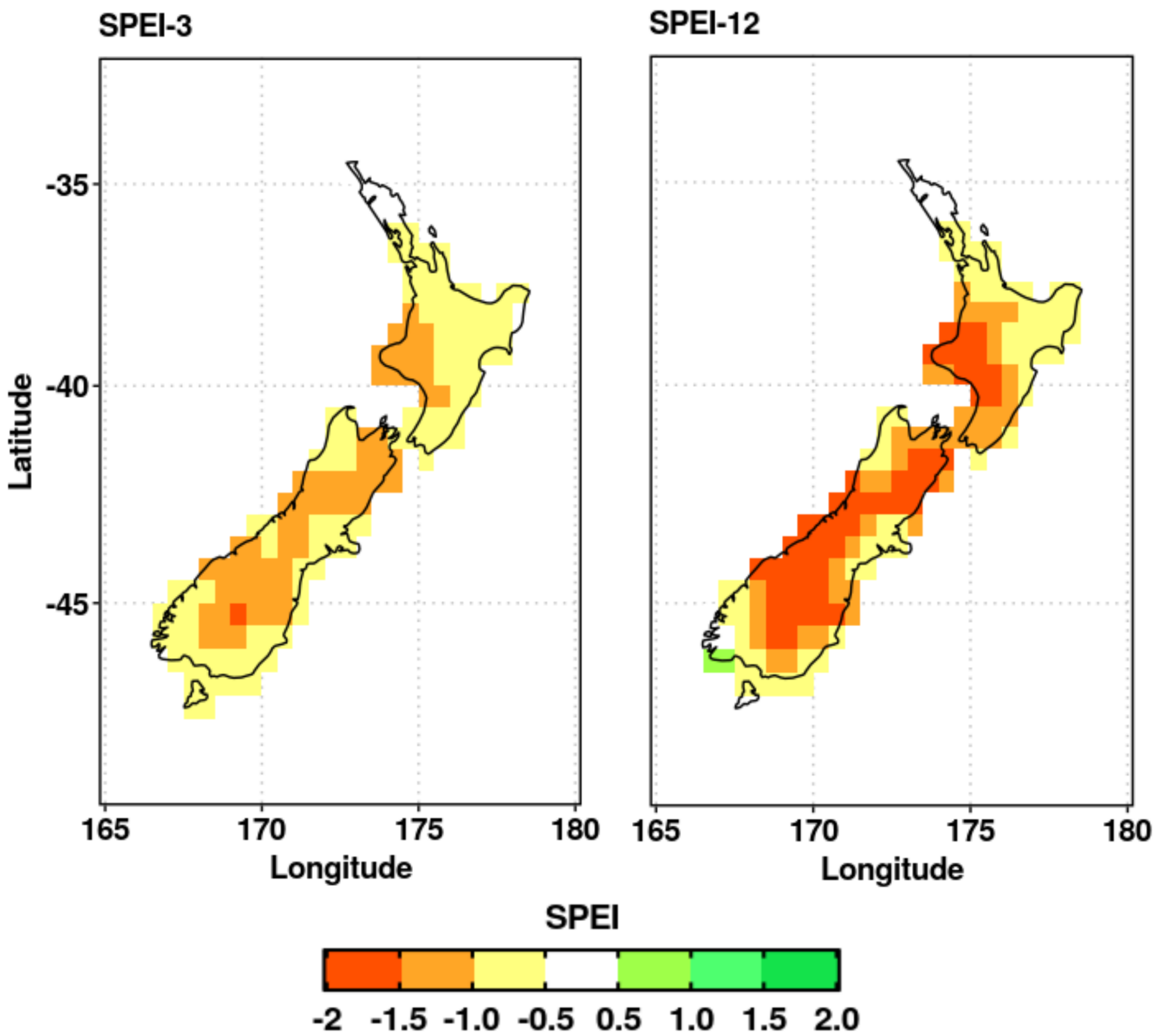

Figure 5.2: Average nationwide SPEI-3 (left) and SPEI-12 (right) for the period July 2007 to June 2008, representing a period of drought identified by Salinger and Porteous (2014)

The issues raised in the preceding sections on the performance of the SPEI-3 at monitoring hydrological drought have important implications for the management of drought across New Zealand. In particular, the use of a two month accumulation period for the SPI in the NZDI is of interest (Mol *et al.*, 2017). The smaller accumulation periods have evidenced an inability to track the impact associated with the passage of water deficits through the terrestrial water cycle over New Zealand, in particular across heavily regulated catchments or catchments were storage is important, such as those influenced by dams, groundwater or snow. Similar findings are noted by Lorenzo-Lacruz *et al.* (2010) and Vicente-Serrano and López-Moreno (2005) across the Iberian peninsula and the Mediterranean. The smaller accumulation periods were however capable of monitoring hydrological drought across unregulated catchments with little natural storage (Lorenzo-Lacruz *et al.*, 2010; Szalai *et al.*, 2000; Vicente-Serrano and López-Moreno, 2005). Therefore the use of SPI-2 in the NZDI creates uncertainty in its ability to track hydrological drought over New Zealand and highlights the potential need for regional specific accumulation periods rather than a nationwide index. The use of soil moisture deficits and PED in the NZDI, together with the noted framework of the NZDI being directed towards agricultural drought monitoring (Mol *et al.*, 2017), means that the uncertainty mentioned above may be somewhat mitigated. However it does indicate that more formal testing may be warranted using the NZDI, particularly if its usage is extended into hydrological drought monitoring. This reiterates the comments by Lloyd-Hughes (2014) that drought research should be placed within the specific context of the type of drought being investigated, and the methodology not incorrectly applied to other drought types.

Despite the possibility the SPEI-3 is inadequate at capturing hydrological drought, the advantages of the SPEI-3 should not be understated. The SPEI-3 does show clear detection of drought onset, which is particularly beneficial in the preparedness for drought events. Early detection of drought onset is seen in the hydro-electrical drought of 1992 and the Auckland reservoir droughts of 1993/1994 (Figure 4.17; Table 4.1). Similar comments are noted by Lorenzo-Lacruz *et al.* (2010), with shorter time scales of SPEI revealing greater sensitivity to climatic variability, thus providing early detection. The small accumulation periods are also beneficial at capturing seasonal components of the hydrological water cycle, as illustrated by the separation of seasonal drought conditions in the current research (Figure 4.9; Figure 4.10). While the SPEI-3 may not be able to adequately capture the snowmelt period across the Southern Alps, which is further evidenced in international research (López-Moreno *et al.*, 2013), the SPEI-3 still has utility in understanding how seasonal changes in precipitation and evapotranspiration affect different catchment types. The investigation into the SPEI-3 does provide interesting insight into the operation of hydrological droughts over New Zealand and has important implications for the use of smaller accumulation periods in the NZDI.

5.2.5 Summary of Temporal and Spatial Variability of the SPEI

The findings in the current study further enforce existing research around the performance of different accumulation periods of both SPI and SPEI: the one month accumulation period can track changes in precipitation well but is unable to capture the antecedent conditions of the catchment such as groundwater and soil moisture, thus is better suited to tracking meteorological drought. Snow storage and storage within hydroelectric dams may play a significant role in alleviating summer hydrological drought conditions across the South Island. These winter droughts have been found in the current research to play a vital role in drought development, both with the number of drought events and the number of strong events often occurring across winter and early spring, requiring any hydrological drought index to be capable of tracking this storage. This is highly specific to individual catchments, depending on the relative influence of catchment characteristics to the hydrological cycle. The range of catchment types over New Zealand suggests the use of multiple indexes may be preferable. Further, the use of different methodology and threshold levels means comparisons between research findings is difficult and non-identification under the SPEI-3 is not necessarily indicative of its poor performance.

5.3. Environment to Climate Analysis

5.3.1 Introduction

The following section analyses the relationship between the SPEI-3 and IVT over New Zealand. This analysis is performed using an environment to climate analysis, whereby groupings of SPEI-3 are developed before investigating the IVT magnitude and direction anomalies which concurrently occur with the SPEI-3 groupings. This analysis is first investigated on a New Zealand wide scale, before narrowing into a regional analysis over New Zealand. The relative influence of precipitation and PET is inspected on a regional scale with the identification of regions whereby PET appears to be of greater dominance to drought development. Possible explanations of drought development linked to changes in wind belts in the wider region are discussed alongside the relative influence of anticyclonic conditions, both as a mechanism for higher temperatures and as a blocking mechanism for the transport of moisture. Unique regional characteristics of moisture transport are also discussed concerning the development of drought. The influence of land-falling atmospheric rivers is also discussed, highlighting areas of future research relating to the significance of these events to the northern regions of the North Island.

5.3.2 New Zealand Droughts and IVT

5.3.2.1 Moisture Transport - Anticyclonic Activity

A common feature over many New Zealand wide drought events is the decline in westerly movement of moisture (Figure 4.5; Figure 4.8; Figure 4.10). The flow of moisture along a west to east trajectory is typically seen across New Zealand (Sturman and Tapper, 2006). This is possibly associated with both a general shift in the passage of moisture over New Zealand (shifting of poleward moisture transport) (Fitzharris and Hay, 1991; Khatep *et al.*, 1984; Salinger *et al.*, 1995), as well as event specific systems such as blocking highs over particular areas of the country which act to interrupt the movement of moisture over the country (Salinger and Porteous, 2014).

Moisture transport typically follows that of the dominant atmospheric pattern which is prevalent during each season (Liu and Stewart, 2003). Over the Mediterranean, Şahin *et al.* (2015) note that the displacement of storm tracks by anticyclonic and cyclonic activity determined drought conditions over the Mediterranean. A strong seasonal aspect was found by Şahin *et al.* (2015), with less moisture transport during summer as a result of displacement by anticyclonic conditions linked to increased frequency of drought occurrence. For New Zealand, the dominance of anticyclonic activity over the summer months across the North Island and winter months over the South Island (Salinger and Porteous, 2014) means that less moisture transport is to be expected during both summer and winter months over the North and South Islands respectively. As a result, drought events might be more likely to occur during these seasonal conditions. Such expectations are largely borne out in the results (Figure 4.10). The presence of anticyclonic movement in the moisture transport during July and August along the bottom of the South Island (Figure 4.10) is further evidence of the positioning of high pressures systems following the findings of Salinger and Porteous (2014). In particular, February is noted by both Salinger (1995) and Salinger and Porteous (2014) to be a dominant month for anticyclonic flow over the west of the North Island and north and east of the South Island, with IVT movement showing a clear anticyclonic flow stationed off the east coast of the North Island in the current research (Figure 4.10).

Strong negative SPEI-3 over the North Island in December is a response to the November IVT anomalies (Figure 4.9, Figure 4.10). However January SPEI-3 conditions reveal positive values over East Cape and Northland, and weaker negative SPEI-3 values during February over the North Island (Figure 4.9). With declines in IVT during these periods and the preceding two months (Figure 4.10), the lack of direct response to changes in IVT in the SPEI-3 indicates the increased presence of other factors, such as PET, in the generation of negative SPEI-3 values during North Island summers.

A closer connection between IVT declines and negative SPEI-3 is visible under the top quantile events over the North Island (Figure 4.6; Figure 4.8), in particular with declines in westerly wind flow noted by Ummenhofer and England (2007) and Ummenhofer *et al.* (2009). The declines in domain average IVT magnitude, while statistically significant at the 5% level (Table 4.2), cannot be ruled out as being the result of a highly unique event due to the small sample size of the top quantiles (n = 4) (Section 3.5.3). A similar disconnect between IVT magnitude and SPEI-3 values to that seen across the North Island summers is also seen across Central Otago and the East Coast of the South Island (Figure 4.9, Figure 4.10), noted regions of high PET rates, suggesting a greater influence of PET across these regions during dry periods (Macara, 2015; Macara, 2016a). Southland and the West Coast regions show closer agreement between IVT declines (Figure 4.10) and negative SPEI-3 values during winter periods (Figure 4.9). The relationship between IVT declines and negative SPEI-3 values thus reveals a close coupling with precipitation over Southland and the West Coast, as well as less influence of PET which is similarly noted by Macara (2013) and Macara (2016b).

5.3.2.2 Moisture Transport - Jet Streams

As noted by Peterson *et al.* (2013), most droughts are either associated with persistent anticyclone activity or changes in the positioning of subtropical dry zones. Changes in the Hadley cell for example were shown by Şahin *et al.* (2015) to result in an extension of the subtropical dry zone over the Mediterranean Basin. In turn, this was identified as a process contributing to dry conditions across the basin, particularly over winter (Şahin *et al.*, 2015). Similar, Rippey (2015) found that a strong polar jet stream, which was displaced northward, resulted in a continuous flow of moisture across Canada and away from the USA during winter. Subsequently, the reduction in moisture over the winter period resulted in drought onset across large areas of the USA in 2012 (Rippey, 2015). Across New Zealand, the poleward movement of moisture transport can be added to the mechanisms associated with drought occurrence for the country (Ummenhofer and England, 2007). The increased band of moisture flux below New Zealand does show signs of increasing in strength when associated with drought conditions over the North Island for the top quantiles and during summer months (Figure 4.8; Figure 4.10). On a seasonal basis, summer months show increased moisture flux across the bottom of the South Island, concurrent with decreased flow across the top of the North Island, in opposition to the more uniform declines in moisture flux across the entire country in other seasons (with the noted exception of June) (Figure 4.10). The movement of this moisture band can be seen more clearly in Figure 4.3, with the increased moisture flux below the South Island visible across the summer months.

As noted by Khatep *et al.* (1984) and witnessed by Ummenhofer and England (2007), strengthening subpolar westerlies are witnessed across the bottom of the South Island during dry months, creating a passage of moisture away from the country. Concurrent with these strengthening winds during dry years in the work of Ummenhofer and England (2007) are decreased westerly winds over the North Island, similarity noted in the current study when investigating summer drought months over the North Island (Figure 4.10). This is further evidenced in the work of Ummenhofer *et al.* (2009) where increased strength of westerly winds across the bottom of New Zealand are present alongside decreased westerlies over the North Island during summer. Additionally, Tait and Fitzharris (1998) note that the dominance of high pressure systems over the north of New Zealand displaces the belt of westerlies to the south of the country, resulting in relatively low precipitation. Similarly, when this belt of westerly movement covers the country, increased precipitation is witnessed across the west coast of both islands (Tait and Fitzharris, 1998). Finally, Clare *et al.* (2002) noted weaker westerly winds associated with a weaker subtropical jet when investigating Southern Alp snow lines: composite maps of mean drought conditions across Southland, West Coast and Central Otago similarly show these weaker westerly winds (Figure 4.20).

Changes in moisture as a result of changes in the subpolar westerly have been linked to wider changes in large scale circulation pattern, such as ENSO and the Southern Annular Mode (SAM) (Ummenhofer *et al.*, 2009). Additional changes in wider atmospheric conditions are also likely to be responsible, such as a poleward shift of the Southern Hemisphere jet which was noted by Harrington *et al.* (2014) to be the drought causing mechanism of a large drought in Northland in 2013. Analysing these fluctuations in wider teleconnections is beyond the scope of this thesis, therefore drawing out the influence of these changes versus the presence of persistent high pressure systems is unable to be made for the droughts identified in the present study.

Across New Zealand, it should be noted that in support of drought development being associated with seasonal anticyclonic systems rather than interannual shifts in wider teleconnections is the work of Mojžíšek (2005) where precipitation variability (South Island only) was largely governed by local circulation influences rather than large scale patterns. While New Zealand is not isolated from large scale patterns, its complex topography and coastal orientation likely mean that the interaction of these large scale patterns and their various configurations with the strong local climate influences are of more relative importance than that of the large scale pattern itself. As highlighted by Dettinger and Diaz (2000), a closer connection may be seen between hydrological drought and climate indices than has been shown to exist with climate indices and meteorological drought, particularly over New Zealand (Gordon, 1985; Mullan, 1995; Salinger, 1995; Salinger *et al.*, 2004). This possible closer connection offers an additional avenue of future study concerning hydrological drought.

5.3.3 Regional Droughts and IVT

5.3.3.1 Upper North Island

Both the Auckland/Waikato and Northland regions reveal a stronger susceptibility to declining northerly flow, or an increased southerly from semi-stationary high pressure systems to the west of the North Island which is statistically significant for the 90th quantile (Figure 4.21; Table 4.5). The presence of these systems is noted by Kidd (2015), Salinger (1995) and Salinger and Porteous (2014) to be a drought causing mechanism, and the identification of moisture direction anomalies supports this hypothesis. The presence of this blocking high pressure system not only explains the absence of moisture over the region, but also provides further detail on the lack of direct connection identified between IVT and SPEI-3 conditions: the high pressure system will also act to increase temperatures across the region as a result of the downward motion associated with the anticyclonic flow (Colucci, 2015).

A decline in moisture from the subtropics (i.e. a declining northerly) may also be the source of the directional anomaly witnessed in Figure 4.21. This may be the result of a decline in the frequency of precipitation from tropical cyclones which affect the area (Rosier *et al.*, 2015). As noted by Harrington *et al.* (2014), the absence of moisture from the tropics for the Northland region was a mechanism associated with the development of drought, which was further linked to the poleward movement of the subtropical moisture belt, which is often associated with decreased moisture during the summer period (Khatep *et al.*, 1984).

As highlighted by Dean *et al.* (2013), Jiang *et al.* (2011) and Rosier *et al.* (2015) moisture from tropical regions may take the form of large episodic events. A reduction in the number of these events would be of more importance than the anomalous conditions of moisture itself due to their episodic nature. Moisture transport has been shown in numerous studies (Gimeno *et al.*, 2014; Paltan *et al.*, 2017; Trigo *et al.*, 2013) to often take the form of long corridors of vapour transport, often termed atmospheric rivers. The absence of this transport has been suggested to be a mechanism for drought (Gimeno *et al.*, 2016), while the return of these atmospheric rivers has also been linked to the cessation of drought events (Dettinger, 2013). It is noted by Paltan *et al.* (2017) that areas where atmospheric river driven precipitation contributes significantly to the annual water supply will experience strong hydrological droughts where the absence of atmospheric rivers is witnessed. While in its infancy, current research suggests that New Zealand is likely to experience a significant portion of its rainfall from these atmospheric river events (Kingston *et al.*, 2016a; Paltan *et al.*, 2017; Zhu and Newell, 1998).

Alternatively, moisture tracking research will also shed light on the sources of moisture to these upper North regions, such as research using a Lagrangian approach to track air parcel movement via back trajectory analysis. Investigations into moisture sources over Europe and in particular the Iberian peninsula have revealed that significant sources of moisture are provided by the Mediterranean Sea together with the North Atlantic corridor from the Gulf of Mexico to the Iberian Peninsula (Gimeno *et al.*, 2010). Blocking of these moisture sources via steering from low pressure systems and changes in wider teleconnections were identified as being the cause of the 2011-2012 winter drought over the Iberian Peninsula (Trigo *et al.*, 2013). Similarly, over New Zealand, an analysis of moisture sources could allow for more focused research on the effects of blocking anticyclonic activity or ridging effects (Gibson *et al.*, 2020) which act to prevent the transport of this moisture. Such research would also enable greater insight into moisture sources for regions over New Zealand, particularly the relative contribution of moisture sources from the Tasman Sea and the Pacific Ocean, and evaporation sources from continental Australia.

5.3.3.2 East Cape

The East Cape region is unique in the association between IVT and SPEI-3, with no apparent link to the declining westerly flow nor declining moisture flux that features heavily across New Zealand and regionally (Figure 4.21). A strengthening westerly flow is noted by Salinger and Porteous (2014) to be a drought causing mechanisms over the East Cape region. The ranges to the west of East Cape act similarly to the Southern Alps, with foehn winds dominating under westerly winds, bringing warm and dry winds to the region with a subsequent increase in evaporation (Sturman and Tapper, 2006). This suggests that across the East Cape region temperature (and therefore PET) plays an important role in the development of drought conditions. While the impacts of low precipitation over the region may be ameliorated by low PET (Kingston and Treadwell, in press), high PET does appear to drive drought events when IVT magnitude over the East Coast is large. Increased temperatures, particularly in summer, may be resulting in increased PET driven drought across the region (Figure 4.24; Figure 4.25, Figure 4.26; Figure 4.27). This is an expected response following general comments by Spinoni *et al.* (2017), where warmer summer temperatures drive more negative SPEI-3 values via increased PET. The East Cape region is identified by Kingston and Treadwell (in press) as highly unique, with PET shown to ameliorate drought. The present discussion does not support this, suggesting the East Cape region warrants further investigation.

The increased frequency of droughts during westerly dominated winds (Mosley and Pearson, 1997) was earlier suggested as the outcome of foehn wind effects, with warmer and stronger winds leading to increased PET over the region, driving drought. The findings of Kingston and Treadwell (in press) suggest decreased precipitation is concurrent with decreased PET across East Cape. Conversely, increased precipitation would be concurrent with increase PET. Spinoni *et al.* (2015) noted that a moderate increase in drought is seen in those regions experiencing significant PET increases alongside precipitation increases over Central Europe. The increased PET can counteract and shift the trend to increased drought occurrence, as PET increases are greater than those of precipitation (Spinoni *et al.*, 2015).

Across the East Cape, the increased moisture flux may signal increased precipitation, which is counteracted by the increases in PET, possibly as a result of increased temperatures and wind speed from foehn winds noted earlier. However, this foehn effect should result in both decreased precipitation (with precipitable water falling on the windward side of the East Cape region) and increased PET (an outcome of the warmer winds). Possible explanations of this disconnect may lie in the indirect relationship between precipitation and IVT magnitude (Gimeno *et al.*, 2010), or an outcome of increased temperatures from the foehn winds driving warmer air temperatures and subsequently a greater capacity to hold moisture (Sturman and Tapper, 2006). In particular, Lu *et al.* (2014) note that the humidity was more important than the lack of precipitation to drought development, which results in increased moisture holding capability in the atmosphere. Regardless, the interconnected relationships between atmospheric moisture, temperature, precipitation and drought over the East Coast region provides an interesting avenue for future study.

5.3.3.3 East Coast of South Island

The East Coast region lies in the lee of the Southern Alps, providing a natural barrier to the flow of moisture from the west, with the composite IVT fields during the 90th quantile of East Coast events highlighting the significance of temperature driven drought to the region by the presence of anticyclonic flow to the east of the South Island which results in small decreases in atmospheric moisture (Figure 4.21). This decrease in IVT magnitude is particularly evident during winter period droughts for the East Coast region (Figure 4.25). Additionally, droughts over the region are the second most frequent across all nine regions of New Zealand, occurring most often in the autumn period (Figure 4.18; Figure 4.23). The frequent occurrence of drought events over the East Coast, which occur concurrent with small declines in IVT magnitude, indicate the region is sensitive to relatively minor declines in precipitation and suggests that PET plays an important role in drought development for the East Coast. The apparent response of PET in the SPEI-3 is similar to that experienced in the study by Spinoni *et al.* (2017) over continental Europe, where differences between SPI and SPEI were strongest in summer, driven by the temperature increase. This increasing divergence between indexes illustrates the importance of PET during warm periods as a result of the increased temperatures driving PET.

The East Coast region is noted as being of increasing risk to drought (Mullan *et al.*, 2005). This increase is likely a response to decreases in precipitation over the region as shown by Salinger and Mullan (1999). However, as noted by Stagge *et al.* (2017) over Europe, the inclusion of temperature via PET in drought indexes (SPEI) results in a further increase in drought risk to regions showing precipitation driven drought. A similar mechanism is therefore likely playing out over the East Coast region, with both decreased precipitation and increased temperatures resulting in increased drought across the region.

The possibility that decreased precipitation and increased temperature are concurrently occurring across the East Coast region is further reinforced by the identification of the East Coast as a specific temperature region by Salinger and Mullan (1999), alongside the evidence of Kingston and Treadwell (in press) suggesting the possibility that such drier and warmer climates are influenced by PET changes more than that of precipitation. Concerning precipitation variability over the region, Mojžíšek (2005) noted increased strength in the westerly flow resulted in increased precipitation to the west and southwest of the South Island and occurred concurrently with negative SPI values across the East Coast region. However, the current research does not support this observation in a purely moisture related context, with mean drought conditions over the East Coast region revealing little change in IVT direction (Figure 4.20), and the 90th quantile events revealing decreased westerly flow of moisture over the middle of the country (Figure 4.21). Possible explanations again lie in the influence of PET over the region. This influence of PET to the detection of drought warrants further discussion, in particular around the disconnect between PET and AET. As noted in Section 3.3, across water limited environments AET is restricted by the availability of moisture for evapotranspiration processes (Manning *et al.*, 2018). The calculation of PET on the other hand is not, and across these environments a disparity between AET and PET emerges, with PET revealing increased available energy rather than increased drying of soil (Manning *et al.*, 2018). For areas such as the East Coast, where strong summer time temperatures exist alongside low summer rainfall (Macara, 2016a), this disparity may explain the disconnect witnessed between atmospheric moisture and drought detection (Figure 4.19; Figure 4.20). The detection of drought in the current research may be artificially exaggerated due to the use of PET, resulting in drought detection which does not exist in reality, thus giving the disconnect between atmospheric moisture and SPEI-3 values.

5.3.3.4 Orographic Effects

It is important to note the effect that the Southern Alps and the Te Urewera and Raukumara mountain ranges may have with atmospheric moisture. As noted by Sturman *et al.* (1999), the interaction of synoptic weather systems with the mountain ranges over New Zealand produces distinct patterns of wind and rainfall. The decrease in westerly moisture flow seen across the West Coast during East Coast droughts (Figure 4.21; Figure 4.24) results in weaker westerly winds forming against the Southern Alps, reducing the possibility that sufficient turbulence can be generated, and therefore less likelihood of precipitation falling in the lee of the Southern Alps.

The importance of temperature to the moisture-precipitation relationship is a further indication of the importance of PET to the calculation of drought conditions, and again suggests the stronger influence of temperature (and therefore PET) over the Central Otago, East Coast and East Cape regions. With work by Purdy and Austin (2003) and Purdy *et al.* (2005) revealing the significance of a seeder-feeder mechanism for orographic enhancement of rainfall over the Southern Alps, the possibility remains that low levels of atmospheric moisture may still be resulting in higher levels of rainfall if sufficient synoptic cloud cover exists over the region as a result of onshore advected processes across the regions. Gimeno *et al.* (2010) provides further support for this possible disconnect between atmospheric moisture and precipitation, noting that increases in atmospheric moisture are not necessarily concurrent with increased precipitation.

5.3.3.5 Regional Comparison

A comparison between regions during the top quantile drought events also offers an interesting insight into the regional differences in drought development across New Zealand. At both the north and south ends of the country a disconnect is revealed: droughts in the North Island regions coincide with neutral and positive SPEI-3 values over the south, with droughts in southern regions coinciding with neutral and positive values over the north (Figure 4.22). Declining northerly flow during drought events over Northland and Auckland/Waikato are manifest with similar increased southerly flow across the South Island (Figure 4.21), a possible result of high pressure systems situated off the west coast of the North Island or a poleward movement of the westerly wind belt as discussed earlier. A more direct westerly increase is witnessed during East Cape droughts, resulting in the extension of neutral or positive SPEI-3 values over the West Coast and Southland (Figure 4.21; Figure 4.22). Finally, drought events across the West Coast, East Coast and Southland all coincide with neutral or positive SPEI-3 values across the upper North

Island (Figure 4.22). This indicates the influence of moisture delivery from subtropical (north) and subpolar (south) wind belts, with changes in the movement of moisture along these belts resulting in the north/south dipole drought development across New Zealand. The regional differences in drought development also highlight the multi-faceted aspect of drought development over the upper North Island, and suggests a possible susceptibility to declines in moisture from the Pacific to the north for the upper North Island regions.

5.3.4 Environment to Climate Summary

The preceding section has analysed the relationship between IVT magnitude and direction in association with the SPEI-3 values over New Zealand in an environment to climate approach, by first grouping SPEI-3 into quantiles and monthly occurrences and then examining the associated IVT anomalies. A common feature has emerged from the analysis of IVT, with decreases in IVT magnitude often associated with a decrease in the westerly flow of moisture, and the size of the magnitude decrease also commonly being associated with the strength of this westerly moisture flow decline. Regional variation has emerged, with the North Island typically experiencing stronger declines in IVT magnitude, which occur most often during summer periods, while the South Island reveals weaker IVT magnitude declines which occur frequently during winter periods. On a finer scale, the Southland and West Coast regions appear most susceptible to these westerly moisture flow declines.

The influence of PET becomes apparent over the Central Otago and East Coast regions where a disconnect between drought development and IVT magnitude is seen across the region, while over the East Cape region a strengthening westerly moisture flow and increased moisture flux is associated with drought development. The presence of anticyclonic activity in the Tasman Sea is commonly found in existing research, and the current findings support this. Alongside the development of high pressure systems, possible wider teleconnections may exist, namely around the movement of the subtropical and subpolar moisture belts which carry easterly and westerly moisture transport respectively. Associated with the subtropical moisture belts, the influence of land-falling atmospheric rivers is discussed, with the effects on Northland and Auckland/Waikato regions suggested as a possible avenue of future study, together with an analysis of ridging effects which may prevent the landfall of these atmospheric rivers.

5.4. Climate to Environment Analysis

5.4.1 Introduction

The following section will analyse the relationship between IVT and SPEI-3 using a climate to environment analysis, whereby the wider atmospheric variables (IVT) are first categorised before examining the SPEI-3 during each category. These patterns are investigated over New Zealand as a whole, by evaluating the frequency of nodes during drought events over the country, as well as during the 90th quantile quantile events and the months of January and July. The similarities and contrasts between the SOM results and the composite maps in Section 5.3 are discussed, including supporting evidence of the importance of blocking anticyclonic conditions and the possibility of the importance of northerly moisture fluxes to Northland and Auckland/Waikato. Contrasts are illustrated around the importance of PET to drought development, where the SOM process shows a closer connection between SPEI-3 and IVT fluxes than the composite maps.

5.4.2 New Zealand Droughts and SOMs

5.4.2.1 Weather Typing

The SOM approach in the current study can be compared to other work over New Zealand that falls largely within the weather typing realm. This work, such as that of Gibson *et al.* (2016), Harrington *et al.* (2016), Jiang *et al.* (2011) and Kidson (2000) involves categorising weather patterns into a number of different types, such as the well known Kidson weather patterns. Gibson *et al.* (2016) used the SOM approach to classify 30 different nodes based on the daily MSLP over New Zealand. The node pattern relating to the top left (node 1) and bottom right (node 25) corners of the current research (Figure 4.11) can be seen to loosely correspond to opposite corners of the Gibson *et al.* (2016) nodal map, with high MSLP over New Zealand creating a blocking pattern shown in the reduced moisture flux and decreased westerly moisture flow under nodes 1, 6 and 11 (Figure 4.11; Table 5.2). Nodes 1, 6 and 11 can be also linked to the R blocking Kidson synoptic weather types and LN weather types from Jiang *et al.* (2011) (Table 5.1), of a ridge of high pressure over the South Island and easterlies over the North Island (Kidson, 2000; Salinger and Porteous, 2014). Further, lower MSLP to the south of New Zealand appears to correspond to nodes 23 and 24, with increased westerly flow and moisture in a cyclonic pattern across the bottom of the country (Figure 4.11; Table 5.2). This can be interpreted as belonging to the T and TNW Kidson synoptic weather types (Kidson, 2000) and the W and HNE weather types of Jiang *et al.* (2011), representing low pressure systems to the south of New Zealand (Table 5.1).

Table 5.1: Categorisation of SOM nodes into Kidson weather types and associated typing from Jiang *et al.* (2011). Kidson weather type descriptions are taken from Kidson (2000)

Kidson Weather Type	Jiang *et al.* (2011) Grouping	Node Numbers
Trough Group		
T	W	23, 24
SW	SW	8
TNW	HNE	23, 24
TSW	TSW	Nil
Zonal Group		
H	H	9
HNW	HN	9
W	HN	25
Blocking Group		
HSE	HS	2
HE	HNE	4, 5, 20
NE	NE	12, 18
HW	S	8
R	LN	1, 11

Further work by Gibson *et al.* (2016) linked these changes in MSLP to anomalies of precipitation and PET, where again a correspondence is seen with the nodal scheme in the current research. The decreased MSLP associated with nodes 23 and 24 in the present study are also associated with increased precipitation anomalies over most of the country, while PET remains neutral across the North Island (Gibson *et al.*, 2016). Nodes 23 and 24 reveal weakly negative SPEI conditions across the country, with positive values under node 24 over the North Island, highlighting the importance of precipitation driven drought to most of the country (Figure 4.12). Negative SPEI values over the East Coast and Central Otago regions, associated with decreased PET anomalies in the work of Gibson *et al.* (2016), is therefore further evidence of the importance of PET to these areas as discussed throughout this thesis (Figure 4.12). Linking the occurrence of temperature and precipitation anomalies associated with the Kidson weather types, which appear similar to the nodal patterns (blocking as R, trough as T and TNW), shows increased maximum temperature over the East Coast (further emphasising the influence of PET), while revealing decreased rainfall over the North Island during zonal patterns (Renwick, 2011). Trough patterns reveal differences to the current study and the work of Gibson *et al.* (2016), with increases in precipitation over the entire country and increased minimum temperatures over the North Island (Renwick, 2011). The importance of winter periods is again emphasised in the current study, both on the frequency of drought events throughout winter periods (Figure 4.18), but also in the dominance of nodes during the winter periods, particularly those in the top quantile events (Figure 4.28; Figure 4.29; Table 5.2).

Harrington *et al.* (2016) also used the SOM approach to classify 12 nodes of MSLP over New Zealand during a summer period defined as January, February and March. A similar map was produced by Jiang *et al.* (2013) based on re-analysis data for the period 1958-2010. Again, while the analysis can only be qualitative, the nodal pattern from both Harrington *et al.* (2016) and Jiang *et al.* (2013) does show similarity to the current research, with nodes 1, 6 and 11 in the present study revealing similar characteristics to the high pressure system nodes of Harrington *et al.* (2016) and Jiang *et al.* (2013), while nodes 23, 24 and 25 in the present study revealing similar characteristics to the low pressure system nodes of Harrington *et al.* (2016) and Jiang *et al.* (2013) (Figure 4.11; Table 5.2). Similarly, the frequent appearance of nodes during the top quantile events over North Island regions (nodes 11 and 25; Figure 4.28), as well as during summer periods (nodes 15 and 25; Figure 4.29) highlights the ability of the current SOM nodal map to identify unique climatic causes of drought events (Table 5.2). However, it is important to remember the complexities involved in the spatial development of drought events. As noted by Harrington *et al.* (2016), ignoring this complexity by attributing the occurrence of one or two nodal patterns as the cause of drought onset or severity can result in an oversimplification of the complex variables working together which result in drought development.

The weather typing performed by the SOM also provides an opportunity for further study, such as an investigation into any possible connection between node types and wider teleconnections such as those of the SAM and ENSO. While the categorisation of nodes into the frequency of node occurrence under quantiles and seasons provides useful insight, the broad time step employed in the current study introduces a limitation to the applicability of the SOMs for further analysis, as the reduction of complex sub-daily moisture patterns into monthly means likely results in the loss of important detail. What the current research does provide though is further evidence of the applicability of SOMs to the analysis of both weather typing over New Zealand, similar to the findings of Gibson *et al.* (2016) and Harrington *et al.* (2016), while also providing a first look at the applicability of the method over New Zealand concerning atmospheric moisture. This could be expanded by investigating how nodes may have changed over the time period (such as having more or less IVT flux) rather than simply the number of times they occur in association with drought months (Gibson *et al.*, 2016; Hope *et al.*, 2006).

5.4.2.2 Drought Associated Nodes

The distribution of nodes during droughts months shows a preference towards nodes 1 through 11 (Figure 4.13). However, node occurrence across drought months does occur across almost every node, except for nodes 12, 18, 24 and 25 (Figure 4.13). Node 6 as an example occurs the most frequently alongside SPEI-3 defined drought months (Figure 4.13) and is defined by large declines in moisture flux over the South Island and lower North Island, smaller declines over the upper North Island and large declines in the westerly flow of moisture (Figure 4.11). The node description is an therefore obvious candidate for declines in precipitation (Salinger, 1980a). In comparison to the composite maps of drought quantiles, there is agreement between node 6 and the top quantile, with node 6 occurring during the 95th quantile (Figure 4.14), and most often during winter periods (Figure 4.29). Visually however node 6 is not in agreement with the composite map of drought conditions in the top quantiles (Figure 4.8), although declines in IVT magnitude are the same over the North Island. This lack of agreement may be explained by methodological differences: IVT during the period leading up to drought identification is below the drought threshold (SPEI-3 of -0.8). This is included alongside the IVT conditions during the drought event (where SPEI-3 exceeds the threshold) as one composite map under the environment to climate approach. Thus identifying specific conditions associated with drought becomes difficult as an outcome of this broad temporal merger of IVT fields. The contrast illustrates the benefits of the dual approach of both a climate to environment and an environment to climate approach, with the climate to environment approach revealing details associated with the specific drought months in greater detail that would otherwise not be visible under the composite approach (environment to climate) due to the aggregation of the lead up months (Yarnal and Draves, 1993).

The presence of certain nodes during drought months that are represented by increased moisture flux is further evidence that for particular regions of the country, the absence of moisture flux is not as strongly related to drought onset than it is in other regions. As an example, node 4 is associated with three drought months, yet is represented by both increased westerly IVT directional movement and increased moisture flux over the South Island (Figure 4.11; Figure 4.13), alongside decreased SPEI-3 values across the entire country (Figure 4.12). This disconnect could be the presentation of PET driven drought conditions, with drought onset being driven by temperature increases more than changes in precipitation in the identification of nationwide drought (Kingston and Treadwell, in press). Additionally, it may also illustrate the limitations of trying to match atmospheric variables to drought conditions on the ground, due to the lag period experienced in the onset of drought conditions (Yarnal, 1993).

On a seasonal basis, there is a predominance of nodes 3 through 5 associated with droughts during summer months (Figure 4.13). The lack of a direct identifiable relationship between declining IVT magnitude and negative SPEI-3 values (Figure 4.11; Figure 4.12) again highlights the lack of connection during summer periods between SPEI-3 and atmospheric conditions, similar to comments by Demirel *et al.* (2013) and Wong and Torfs (2013). This inability is likely due to the ongoing issue of the delayed response of drought conditions (Van Loon, 2015), as the hydrological regime attenuates the terrestrial passage of water, creating a delay between meteorological drought and hydrological drought. For example, a clear connection can be seen in the anomalous declines of IVT magnitude and negative SPEI-3 values throughout winter drought events which occur concurrently with nodes 6, 11 and 16 (Figure 4.11; Figure 4.12). This connection matches that seen in the monthly analysis of composite maps for winter and early spring (Figure 4.9; Figure 4.10). However moving into summer hydrological droughts this connection becomes less obvious, highlighting that the impact felt from summer hydrological droughts is often the result of processes occurring many months prior (Van Loon, 2015), and the inability of the SPEI-3 to mimic these hydrological droughts due to the disconnection between PET and atmospheric processes such as atmospheric moisture. Again, composite maps generated from the environment to climate approach reveal similar information (Figure 4.9; Figure 4.10).

5.4.3 Regional Droughts and SOMs

5.4.3.1 North Island

On a regional basis a clear dominance of nodal occurrence is not visible across any particular region nor during any particular month, similar to that seen across New Zealand as a whole (Figure 4.29). For the Auckland/Waikato and Northland regions, node 11 occurs the most frequently, where IVT magnitude has declines alongside a strong decline in the northerly flow of moisture (Figure 4.11; Figure 4.29). This node suggests the lack of moisture from the tropics plays an important role in the development of drought with atmospheric moisture, more so than the absence of moisture itself. Composite maps of regional droughts (Figure 4.20) further support the significance of this nodal type to drought development over the regions. During the discussion in Section 5.3.3.1, the changes in atmospheric moisture over the upper North Island were unable to be distinguished between decreasing northerly flow or strengthening southerly flow associated with the presence of anticyclonic conditions. The SOM approach is similarly unable to distinguish between the two, as nodal types revealing a possible anticyclonic presence (nodes 8, 9 and 10) all feature during drought events across the regions, with node 10 in particular being a common occurrence during the top quantile events (Figure 4.28). The similar patterns seen between nodal types and composite maps for the Northland and Auckland/Waikato regions is further emphasised across the East Coast region. Section 5.3.3.2 highlighted the significance of increased westerly moisture flow and moisture flux (Salinger and Porteous, 2014), which suggested PET driven droughts (Kingston and Treadwell, in press). The SOM further supports the significance of PET driven droughts to the East Cape region, with node 25 being the dominant node during the top quantile events (Figure 4.28).

5.4.3.2 South Island

Across Southland and the West Coast the SOM approach looks to capture the dynamics of IVT conditions associated with drought well, with strong moisture flux and westerly anomaly decreases associated with nodes 11 and 16 (Figure 4.11) which appear similar to the composite maps of mean drought conditions (Figure 4.20) and the 90th quantile events (Figure 4.21). These nodes occur frequently across the regions and during the top quantiles (Figure 4.28; Figure 4.29). The similarity between the environment to climate approach and the climate to environment approach in IVT patterns illustrates that for the Southland and West Coast regions the SOM can capture significant drought events based on IVT conditions. Because temperature patterns over Southland and the West Coast are not as highly localised as those of precipitation (Salinger, 1980a; Salinger, 1980b), the closer association between drought identification and atmospheric moisture anomalies indicates that precipitation is the main driver of drought conditions across the regions. Further, the similarity of the SPI and SPEI results in Kingston and Treadwell (in press) adds additional evidence to the notion that precipitation driven drought is the dominant drought causing mechanism over Southland. Over the West Coast precipitation dominated drought is similarly noted (Mojžíšek, 2005; Tyson *et al.*, 1997).

The Central Otago region is not only frequently affected by declines in precipitation as drought causing mechanisms, but additionally atmospheric evaporative demand which affects drought conditions via increased PET (Kingston and Treadwell, in press). This was illustrated by Kingston and Treadwell (in press) via large differences between drought occurrence and magnitude as well as different spatial expression between SPI and SPEI. The nodal classification offers insight into the atmospheric patterns associated with drought onset as a result of precipitation changes, with the presence of nodes 11 and 16 as a frequent nodal pattern during droughts (Figure 4.29), as well as during the top quantile events (Figure 4.28). Similar, mean drought conditions during composite analysis reveal an association with atmospheric moisture anomalies (Figure 4.20). In contrast, node 3 also features during drought events (Figure 4.29), and is described by increased westerly moisture flow and small increases in atmospheric moisture flux over the region (Figure 4.11). Here declines in IVT magnitude (nodes 11 and 16) may signify precipitation driven drought, while the increases in IVT magnitude alongside drought conditions may signify PET driven drought (node 3), an important factor in the semi-arid region of Central Otago (Cossens, 1987). Because nodes 11 and 16 occur during the top quantile events (Figure 4.28) this may indicate the significance of PET as a second order driver of drought, however the lack of agreement between the composite maps of the top quantile events across Central Otago and the SOM during the same events does not discount the possibility that the SOM process is unable to capture these regional characteristics as discussed earlier.

The East Coast region tells a similar story, with node 6 representing the clear connection between precipitation and drought development represented by decreased flux and westerly moisture movement, and node 4 illustrating PET importance to the region represented by increased flux and westerly moisture movement during drought (Figure 4.11; Figure 4.29). The East Coast region also features heavily in the occurrence of nodes 6, 11 and 16 during winter droughts (Figure 4.29). The heavy presence of the declining westerly flow and IVT magnitude associated with the node occurrence during winter, along with the lack of these nodes occurring during the top quantile drought events, suggests that despite the common occurrence of a lack of moisture during winter, the strongest drought events do occur under different nodes (Figure 4.28; Figure 4.29). This is further evidence of the impact of PET to drought over the East Coast region, with stronger droughts being associated with node 2 and 4, which feature increases in IVT magnitude and westerly flow.

5.4.4 Climate to Environment Summary

The SOM nodal map reveals both similarities and differences to the composite maps produced in Section 5.3. An examination of the nodal map and the occurrence of individual nodes during drought events revealed the occurrence of a large number of nodes during droughts across the country, with little domination of any particular node. This highlights the complexity of drought development over New Zealand, as well as illustrating the difficulty in identifying concurrent drought conditions with atmospheric variables using the SPEI-3. However, a cluster of nodes from 1 through to 11 feature heavily when grouped, both over New Zealand and regionally (Table 5.2). These nodal patterns largely reveal anomalous decreases in moisture fluxes and the westerly flow of moisture, which occur frequently and dominate the top quantile events both nationally and regionally (Table 5.2). Seasonally there is a dominance of nodes 5 and 25 during summer, and nodes 6 and 11 during winter, with winter node occurrence being more frequent than any other season (Table 5.2). Node 2 dominates during the top quantile events across the East Coast region, and reveals minor decreases in IVT magnitude with little directional change, suggesting the influence of PET during these periods as initially revealed in the composite maps (Table 5.2). Similar again to composite maps, node 6 over the East Coast region reveals decreased moisture flux and westerly flow of moisture, illustrating precipitation driven drought across the region.

Table 5.2: Summary table of node occurrence across regions, quantiles and seasons, alongside identification of similarities in node patterns to the work of Gibson *et al.* (2016) and Harrington *et al.* (2016)

Node Number	Region	Quantile	Season	Gibson *et al.* (2016)	Harrington *et al.* (2016)
2	Southland, East Coast	10%	Autumn	d3	c0
3	Lower North Island, Central Otago	20%	Autumn	d2	c0
5	Lower North Island, Nelson/Marlborough	5%	Summer	a1	a5
6	East Cape, East Coast	10%	Winter	e0	c2
11	Northland, Auckland/Waikato, West Coast, Central Otago, Southland	20%	Winter	e1	c3
14	Lower North Island	20%	Spring	a2	a1
16	West Coast, Central Otago, Southland	10%	Winter	e1	c3
25	East Cape	5%	Summer	e5	a0

Additional node dominance is seen with nodes 10 and 11 across Central Otago, West Coast, Southland, Auckland/Waikato and Northland, featuring increased westerly flow of moisture and moisture flux under node 10, with the opposite under node 11 (Table 5.2). In particular, node 11 highlights the potential of anticyclonic blocking over the Northland and Auckland/Waikato regions, while node 10 with decreased northerly flow suggests the influence of moisture from Pacific sources, again featured in the discussion on composite maps in Section 5.3 (Table 5.2). Outside of the nodal range of 1 through 11, node 16 dominates across the West Coast and Central Otago regions, again revealing declines in atmospheric moisture alongside weakening westerly directional flow, while node 25, featuring increased westerly directional flow and moisture flux, is frequent during East Cape drought events (Table 5.2). Agreement is again seen with composite maps of droughts over the regions. Comparatively to the composite maps, the SOM nodal map suggests a closer connection between precipitation and drought development than the composite maps, although this is limited by the use of the SPEI-3. The nodal scheme developed appears qualitatively to align with numerous other studies over New Zealand involving weather typing, suggesting the possible utility that may be gained by further analysis using the SOM method on a finer temporal resolution.

5.5. Summary of Relationship between IVT and SPEI

Table 5.3 provides a summary of the findings on the relationship between IVT and SPEI-3 in the current study. The table summarises the nationwide and regional characteristics between IVT and SPEI-3, including the dominant IVT directional and magnitude anomaly (Table 5.3). The dominant node and seasonal occurrence are also listed, alongside the proposed drought causing mechanisms or likely sources of moisture (Table 5.3). As an example, the East Coast region shows, in summary, no change in IVT direction during drought events (Table 5.3). Declines in moisture flux and a dominance of nodal patterns 2, 6 and 11 exist during droughts (Table 5.3). Droughts occur most commonly during autumn and winter, with the possible mechanisms linked to blocking or riding events together with local topographic interactions (Table 5.3).

Table 5.3: Summary table of relationship between IVT, SPEI-3 and SOM nodal patterns across New Zealand and regionally

Drought Region	IVT Direction	IVT Magnitude	Nodes	Season	Moisture Sources/ Drought Mechanisms
New Zealand	Decline Westerly (N.I.) No Change (S.I.)	Large Decline (N.I.) Decline (S.I.)	1,5,6,11,16	Late Winter, Spring	Blocking/Ridging, Jet Stream Movement
Northland	Increase/Decline Southerly/Northerly	Decline	1,6,9,11,13	Winter	Blocking/Riding, Tropical Moisture
Auckland/ Waikato	Increase/Decline Southerly/Northerly	Decline	5,6,9,11,17	Winter	Blocking/Ridging, Tropical Moisture
East Cape	Increase Westerly	Increase	6,10,14,25	Winter, Summer	Jet Stream Movement, Topographic Interactions
Lower North Island	Decline Westerly	Moderate Decline	3,4,5,11,14	Spring, Winter	Blocking/Ridging, Jet Stream Movement
Nelson/ Marlborough	No Change	Decline	5,6,11	Winter, Summer	Blocking/Ridging, Jet Stream Movement
West Coast	Decline Westerly	Large Decline	7,11,16	Autumn, Winter	Blocking/Ridging
East Coast	No Change	Decline	2,6,11	Autumn, Winter	Blocking/Ridging, Topographic Interactions
Central Otago	Decline Westerly	Decline	3,6,11,16	Autumn, Winter	Blocking/Ridging, Topographic Interactions
Southland	Decline Westerly	Large Decline	2,4,11,16	Autumn, Winter	Blocking/Ridging, Jet Stream Movement

5.6. Summary

The preceding chapter has compared the performance of the SPEI-3 with other accumulation periods of SPEI, which has highlighted the quicker response time of the SPEI-3 to drought onset, at the expense of the ability to track drought conditions through catchments with long memory conditions. This limitation is evident in the current study over the South Island, with the snow storage capabilities of the Southern Alps providing an attenuating effect on the hydrological regime. This limitation of the SPEI-3 was further analysed by investigating its performance in the current study to identify drought events across New Zealand from existing research. In addition, the spatial characteristics of the index, particularly around the performance of the PET component, was investigated against existing research, highlighting regions where PET appears to be an important second order driver of drought development. An investigation of the relationship between IVT and SPEI using both an environment to climate and climate to environment approach further supported the identification of PET importance to the East Coast and Central Otago regions in particular. These regions reveal drought development both concurrent with moisture flux decreases over the region, as well as during periods where moisture flux has increased, with increased moisture flux during drought highlighting the importance of PET as a second order driver.

East Cape was revealed as a unique region for drought development, with increased westerly moisture flow and moisture flux apparent during drought development. Similar to the East Coast comments, this suggests PET as an important driver across the region, although the influence of the rain shadow effect generated by the mountain ranges to the west of the region may also play a part. The Northland and Auckland/Waikato regions highlight competing possible causes in drought development. Persistent high pressure systems alongside movements in subtropical and polar jet streams were unable to be separated, and suggest a possible avenue for further study in conjunction with an investigation into the importance of atmospheric river moisture to the regions. The remainder regions over New Zealand show a more direct connection to drought development, with decreased moisture flux associated with decreased westerly flow of moisture. These common IVT patterns during drought are again attributed to blocking high pressure systems across the Tasman Sea, or wider movements in jet streams to the north and south of New Zealand.

6. Conclusion

This thesis has investigated three research objectives (Chapter 1). These research objectives were addressed by first investigating the wider literature and prior knowledge, with a focus on identifying areas where knowledge is missing which aligned with the research objectives (Chapter 2). After this, methods were developed which attempted to address these objectives (Chapter 3), before results were presented (Chapter 4) and discussed (Chapter 5). In turn, this chapter will summarise how these objectives are met, and future research directions will be presented.

6.1. Research Objective One

The first research objective was the usage of the SPEI-3 to monitor hydrological drought over New Zealand. This was done by investigating the performance of the index with other accumulation periods. The results suggest that the use of the SPEI-3 as a hydrological drought index over New Zealand should be treated with caution. The short accumulation period of the index means that many of the antecedent conditions associated with hydrological drought are not always adequately captured, resulting in a frequent onset and cessation of hydrological drought which may be one longer, multi-period hydrological drought event. However, the need to capture these antecedent conditions is highly dependent on the catchment characteristics. The SPEI-3 appears to show agreement as a hydrological drought index across selected unregulated river basins, but also suggests that regulated and groundwater driven catchments across New Zealand may not be adequately captured. The findings indicate that the use of multiple, regional specific accumulation periods may be preferable to capture the varied hydrological regimes of New Zealand catchments. The findings also have important implications for the usage of the NZDI, which makes use of a two month accumulation period, and suggests that the application of the index to hydrological drought should be treated with caution.

The identification of regions using the SPEI-3 can largely be tied to existing research, with little unexplained deviation between regional identification using the SPEI-3 or other drought indexes. The lack of memory conditions present in the SPEI-3 helps identify regions where PET may be an important second order driver of drought, particularly around the Central Otago, East Coast and East Cape regions. Both Central Otago and the East Coast experience PET driven drought conditions, while over the East Cape region, PET is seen to ameliorate precipitation deficits. Secondly, the use of the SPEI-3 was able to identify drought events noted by other authors. The non-identification of drought events was shown to be the outcome of the use of the nationwide threshold level, alongside methodological differences. The SPEI-3 shows frequent oscillation between drought detection and cessation which illustrates the ability of the index to accurately identify drought onset. The index also showed utility in helping identify the interaction between climatic variables and catchments on a seasonal scale. Across catchments where hydrological drought can have significant effects (such as hydroelectric power and reservoir storage), the ability of the SPEI-3 to detect early onset may be particularly beneficial.

6.2. Research Objective Two

The second research objective was directed towards exploring the relationship between SPEI-3 and IVT over New Zealand and regionally using an environment to climate approach. This investigation was performed using composite maps of IVT for each calendar month alongside composites of the top quantile events. The results indicate drought causing mechanisms fall into one of two categories: blocking effects from anticyclonic systems, or changes in jet stream activity which reduces the transport of moisture across the country. However there is still large regional variation, suggesting localised effects also play a significant role in drought development. Composite maps suggest that drought development in Northland and Auckland/Waikato may be the subject of declines in the northerly flow of moisture, which highlights the need to investigate the annual significance of this moisture to help determine if the blocking of these events may be an important part in the development of drought.

The East Cape region was highlighted as a unique region for drought development, with increased westerly flow of moisture and moisture flux seen across the region during drought events. This was linked to previous research across the region which highlighted a similar theme to drought development. Together with the findings relating to SPEI-3, it highlights the importance of PET driven drought to the region. PET was also identified as important to drought development over the Central Otago and East Coast regions. Composite maps revealed both decreased westerly flow of moisture and moisture flux for these regions, as well as increased westerly flow of moisture and moisture flux during different drought events. With existing research highlighting the potential importance of PET to drought development, the disconnect between increased moisture flux and drought was identified as a possible mechanism for drought development as a result of increased PET.

Other areas such as the West Coast and Southland show a clearer association with decreased westerly flow of moisture and moisture flux with drought development over the regions. An analysis of regional similarities in drought reveals a disconnect between the north and south of the country, with drought conditions over the North Island concurrently occurring with neutral or positive SPEI-3 values across the bottom of the country. The same pattern is seen in reverse when examining southern regions of the country. The disparity is identified as a result of the longitudinal range of New Zealand, with the extreme ends of the country affected by different jet streams: the polar jet stream across the south of the country and the subtropical jet stream over the north of the country.

6.3. Research Objective Three

The third research objective was aimed at further exploring the IVT and SPEI-3 relationship, by using a climate to environment approach to characterise IVT patterns. IVT patterns over New Zealand were categorised using the SOM method. The results of the SOM method are not conclusive, largely as the result of the broad temporal resolution which was necessitated due to the SPEI-3 database. However, the method does show agreement between the nodal map output and with existing literature over New Zealand using the same method, with agreement seen between nodes of atmospheric moisture and MSLP over New Zealand. In addition, the nodal maps also show agreement to the composite maps produced in the earlier part of the thesis, illustrating that the method does show promising results despite the broad temporal resolution.

The results suggest the use of the method may yield favourable results if employed on a daily time step to analyse atmospheric moisture, when performed in conjunction with a wider analysis of atmospheric variables such as MSLP and geopotential height. In particular, the dominance of nodes 1 through 11 show results in line with composite maps of drought conditions over New Zealand and regionally, with the nodal map also able to identify unique regional characteristics such as the dominance of increased westerly flow of moisture and moisture flux over the East Cape region under node 25. Further, the method shows the ability to identify seasonal variation in the pattern of moisture over New Zealand, with node 6 a frequent occurrence during winter drought events over the country. Together, despite the coarse temporal resolution, the method does show promising signs for further research.

Collectively the results have revealed that the use of the SPEI-3 to track hydrological drought across New Zealand may only be appropriate in unregulated catchments, while its usage over heavily regulated catchments should be treated with caution. This highlights the need to use multiple indexes when investigating hydrological drought across New Zealand due to the varied hydrological regimes. The connection between IVT and droughts over New Zealand reveals that a disruption to the westerly flow of moisture and a decrease in the moisture flux is common, which is stronger in areas more exposed to the westerly flow of moisture. Areas in the relative shelter of mountain ranges reveal the importance of PET driven drought, while upper north regions highlight the possibility of tropical moisture sources which may form a significant part of the hydrological regimes across these regions.

6.4. Future Research

Areas of future research which were identified include an investigation into the performance of the SPEI on numerous accumulation periods to identify its performance at modelling hydrological drought across the range of catchment types which exist over New Zealand. Such an analysis would help identify if any single accumulation period is better able to monitor hydrological drought over New Zealand, or if indeed a combination of periods is required to capture the varied regimes over New Zealand.

Future research should also be directed towards investigating moisture transport over New Zealand in association with other atmospheric variables such as MSLP and geopotential height and wind. This would enable quantification of many of the findings highlighted in the current study on the transport of moisture over New Zealand, such as the impacts of blocking anticyclones in the Tasman Sea. Performed in conjunction with an investigation on a wider spatial resolution would additionally enable an understanding of moisture transport implications associated with changes in jet streams to the north and south of the country, which in turn may provide evidence of possible teleconnections.

A detailed investigation into the influence of atmospheric rivers to the hydrological regime over New Zealand could also shed light on the importance of blocking mechanisms which may act to prevent these events from making landfall. In particular, the Northland and Auckland/Waikato regions indicate a possible susceptibility to these events from the South Pacific. This research may also take the form of identifying sources of moisture using a Lagrangian approach. Such research should be directed towards understanding the influence these events have across the regions, while also investigating the role anticyclonic systems in the Tasman Sea have on the movement of these systems via ridging analysis. The relative importance of atmospheric rivers to the regions as a percentage of precipitation would not only aid in the understanding of drought development, but also the wider understanding of the sources of moisture and their relative importance to these regions.

It is hoped that the initial investigation using the SOM method is sufficient to generate further analysis on a finer temporal resolution across New Zealand in a similar manner to the one performed here. As an example of the possible identification of similar nodal types as drought associated nodes, the identification of the winter nodes shows some promise i.e. nodes 6, 11 and 16 are all close in nodal space and share similar characteristics to each other. They also provide a logical connection between declining westerly moisture flow and decreases in moisture flux associated with winter droughts, while additionally matching those composite maps performed earlier in this thesis. The performance on a finer temporal scale could also be assessed alongside an investigation into changes into the characteristics of the nodes throughout time, to identify climate change effects which may be visible, and which would aid in the assessment of drought development across New Zealand under various emission scenarios.

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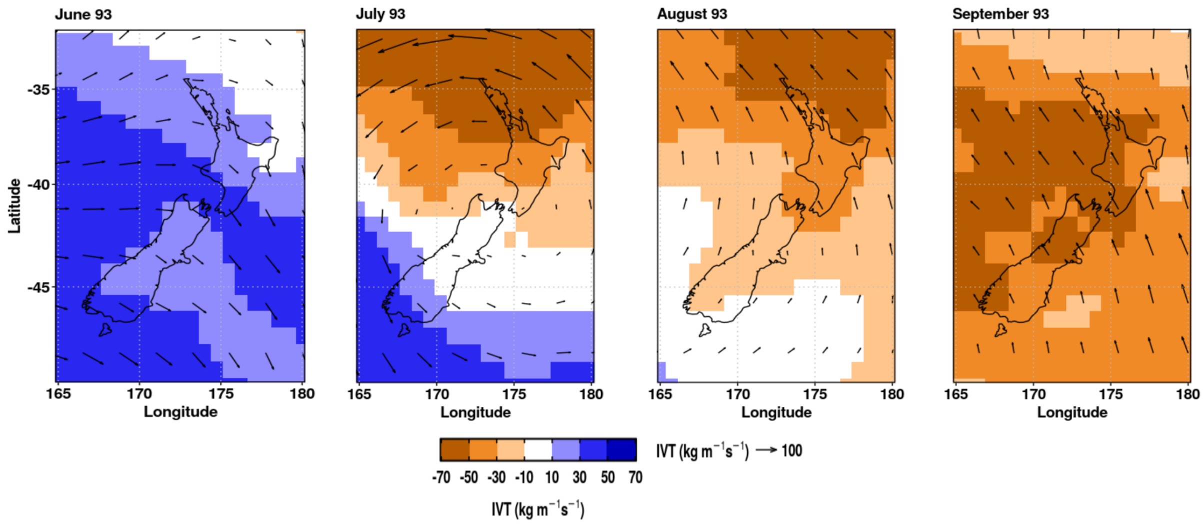
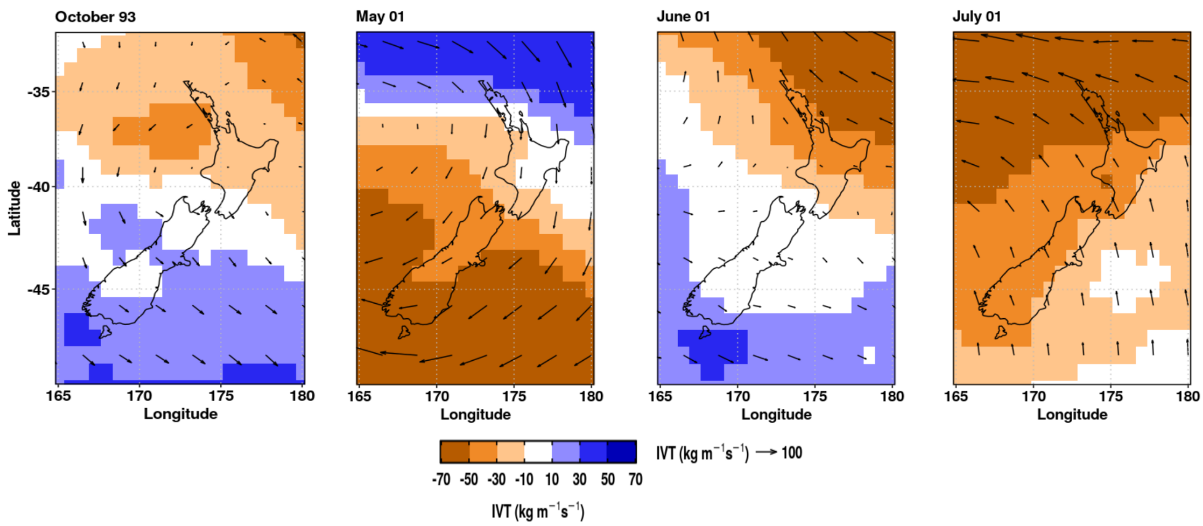
Appendix A: Selection of NZ Wide Quantiles

95th Quantile



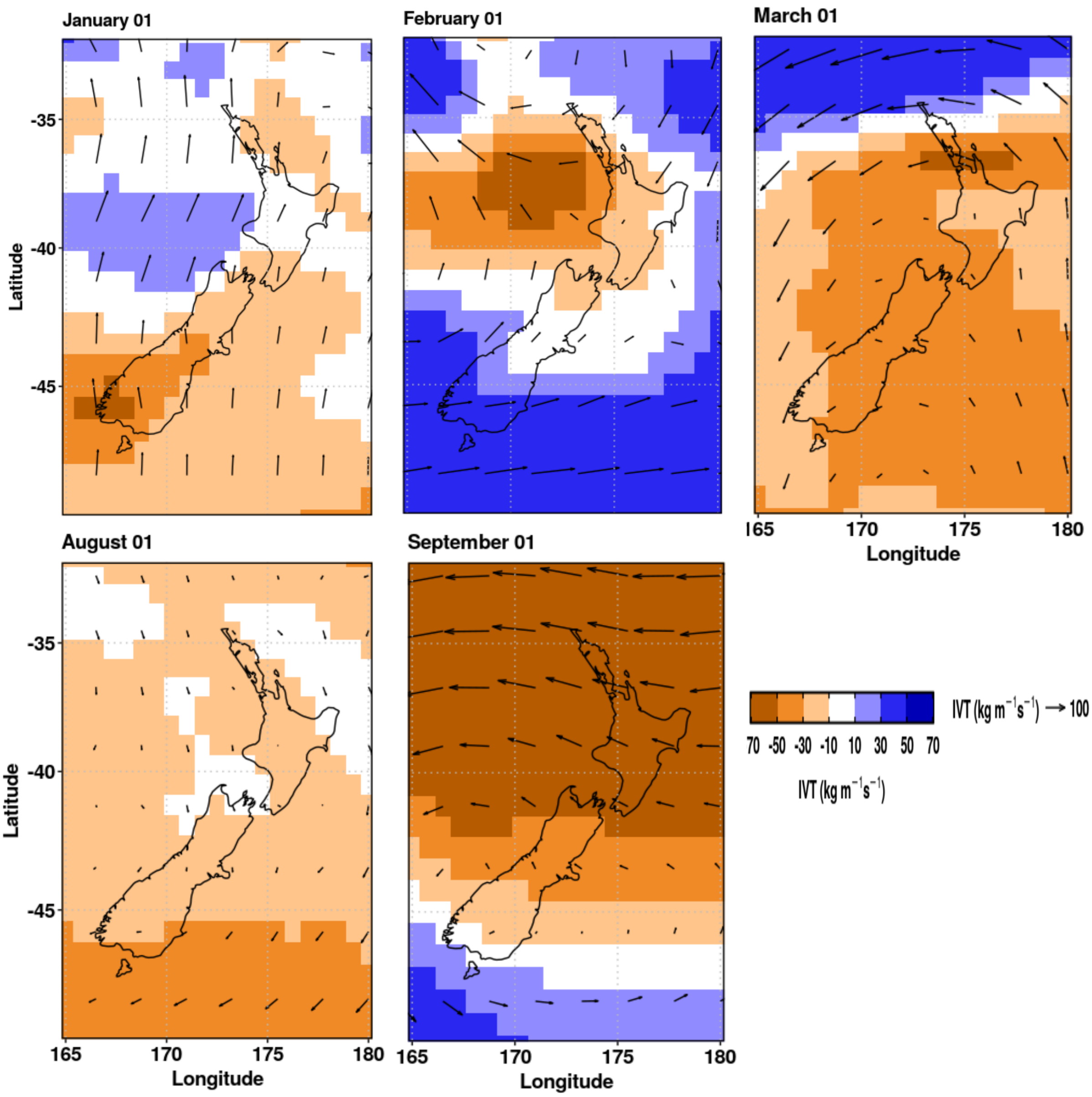
Anomalous IVT Conditions for Individual Months Making up the 95th Quantile

90th Quantile



Anomalous IVT Conditions for Individual Months Making up the 90th Quantile

80th Quantile

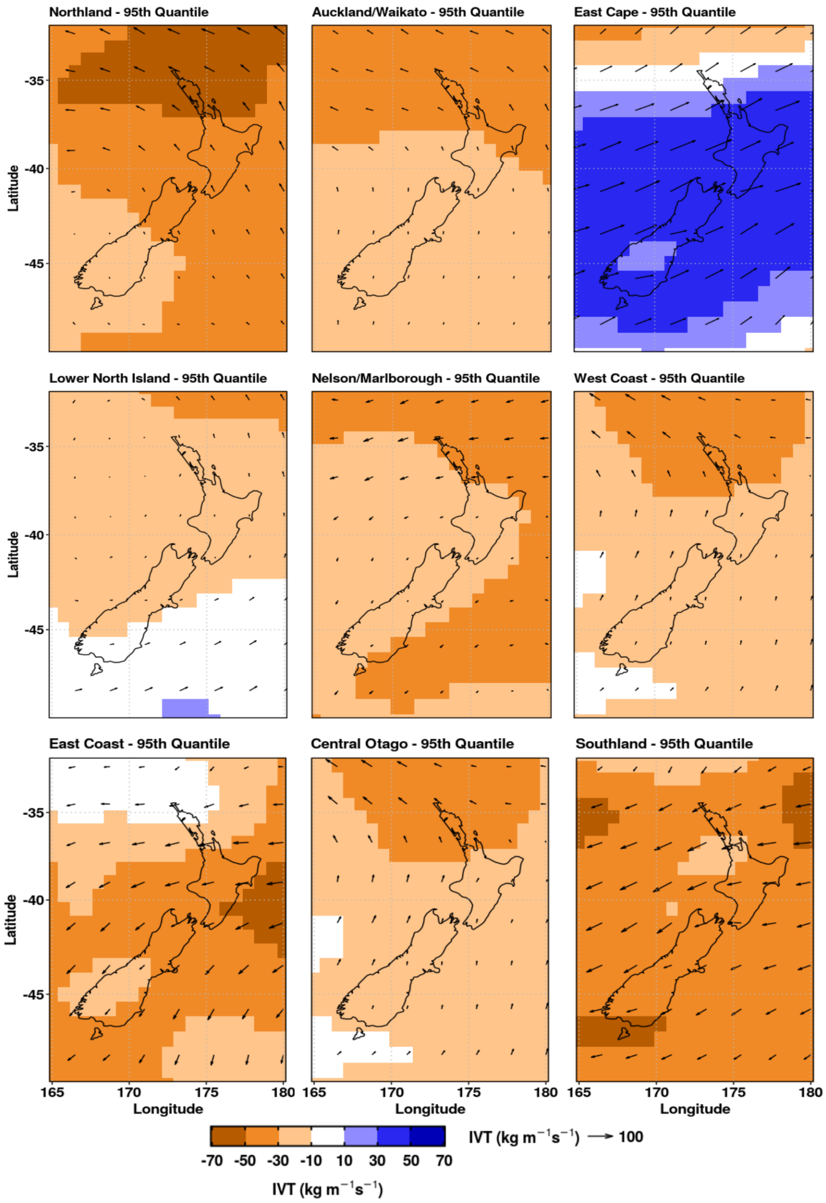


Anomalous IVT Conditions for Individual Months Making up the 80th Quantile

Appendix B: Selection of Regional Quantiles and Months

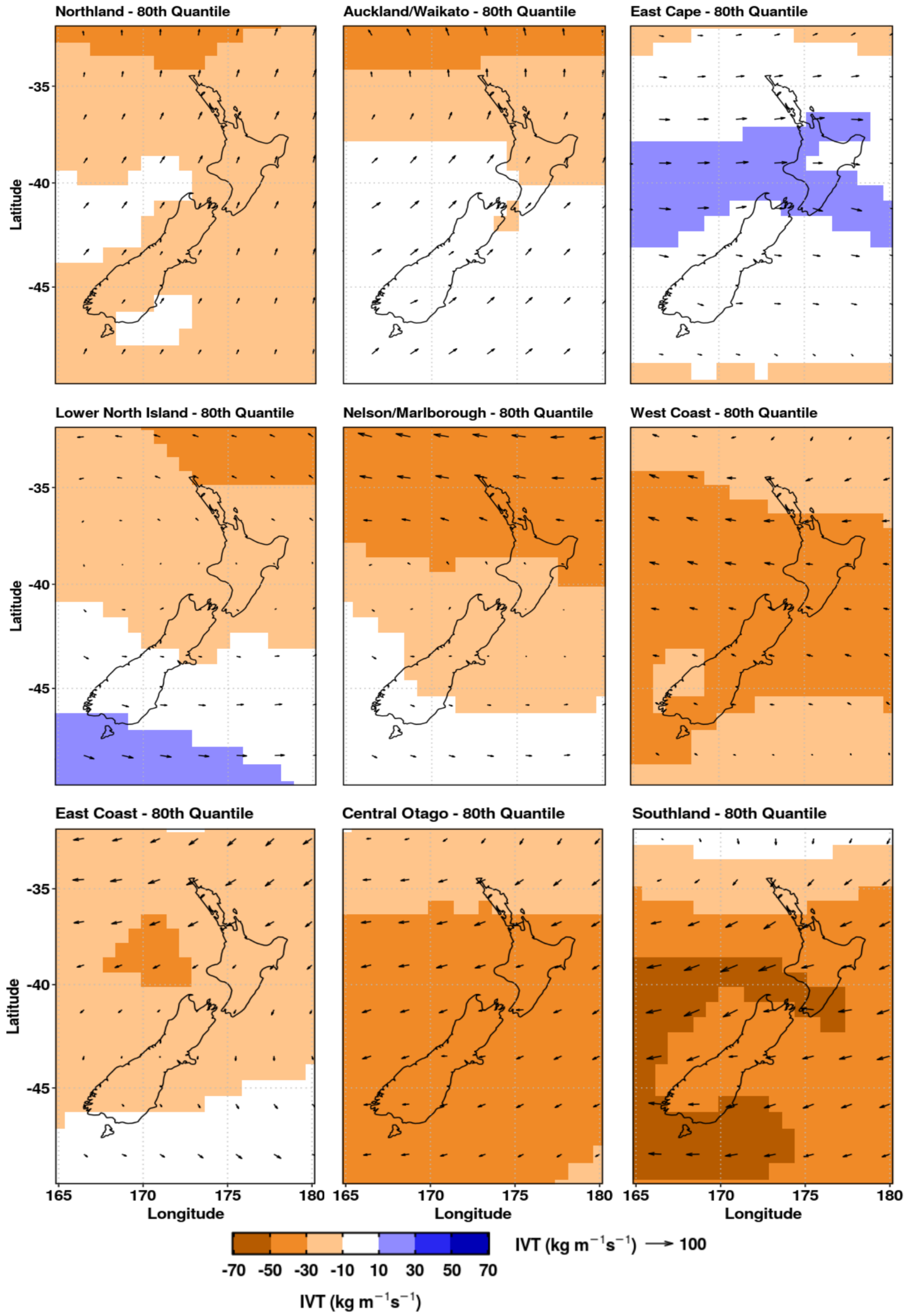
Regional Quantiles

95th Quantile



IVT anomalous conditions for the 95th quantile drought events across all regions

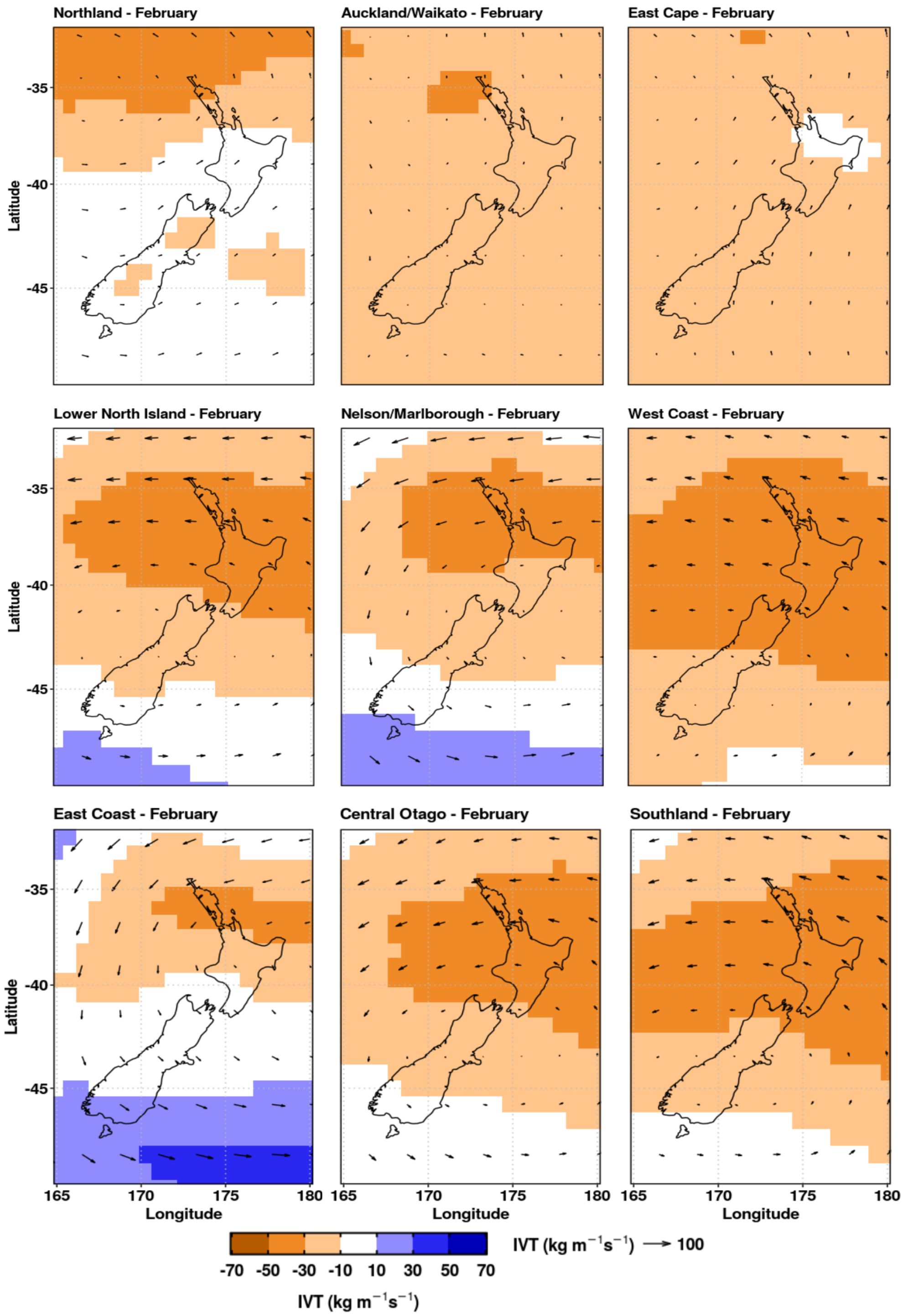
80th Quantile



IVT anomalous conditions for the 80th quantile drought events across all regions

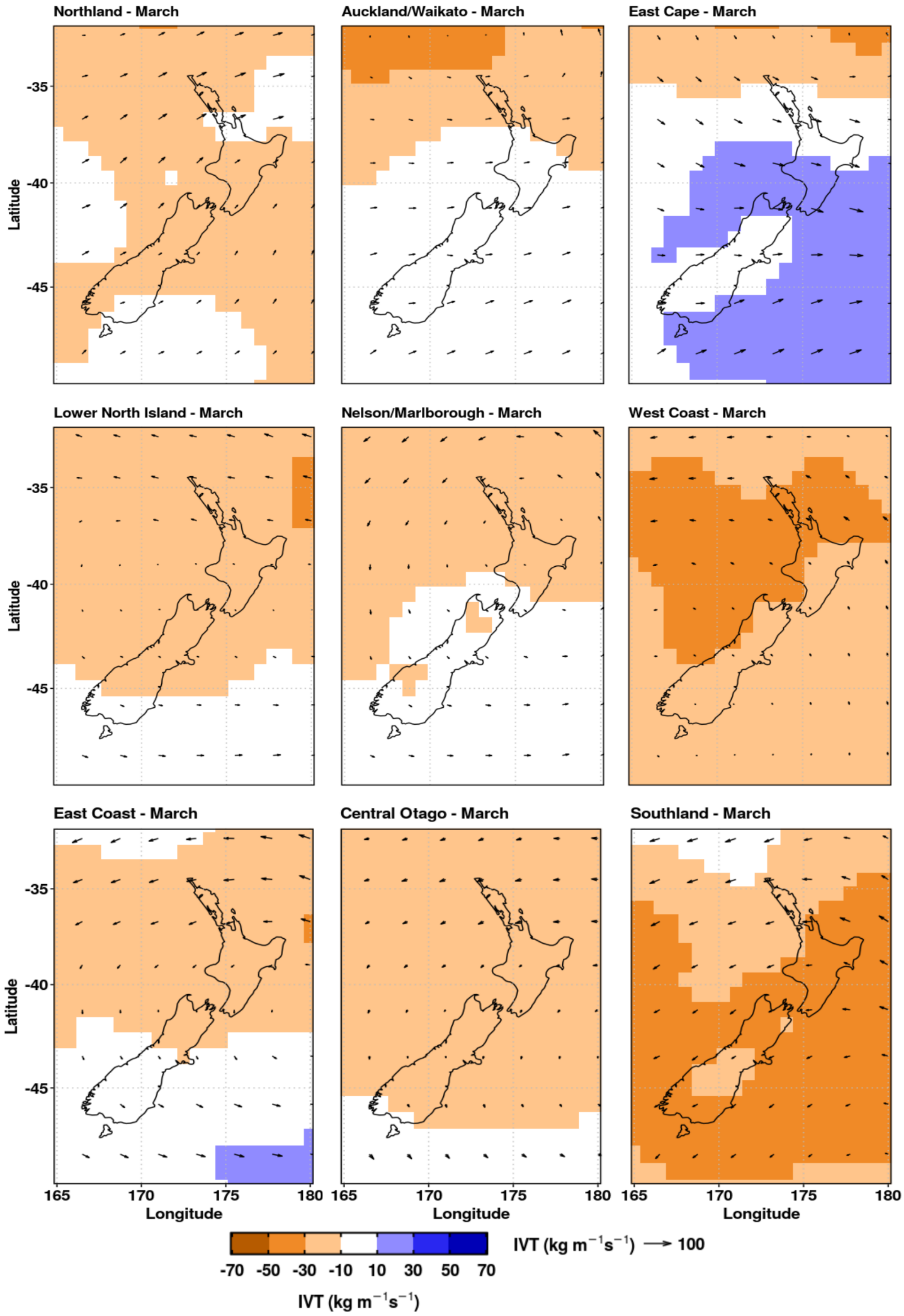
Regional Months

February



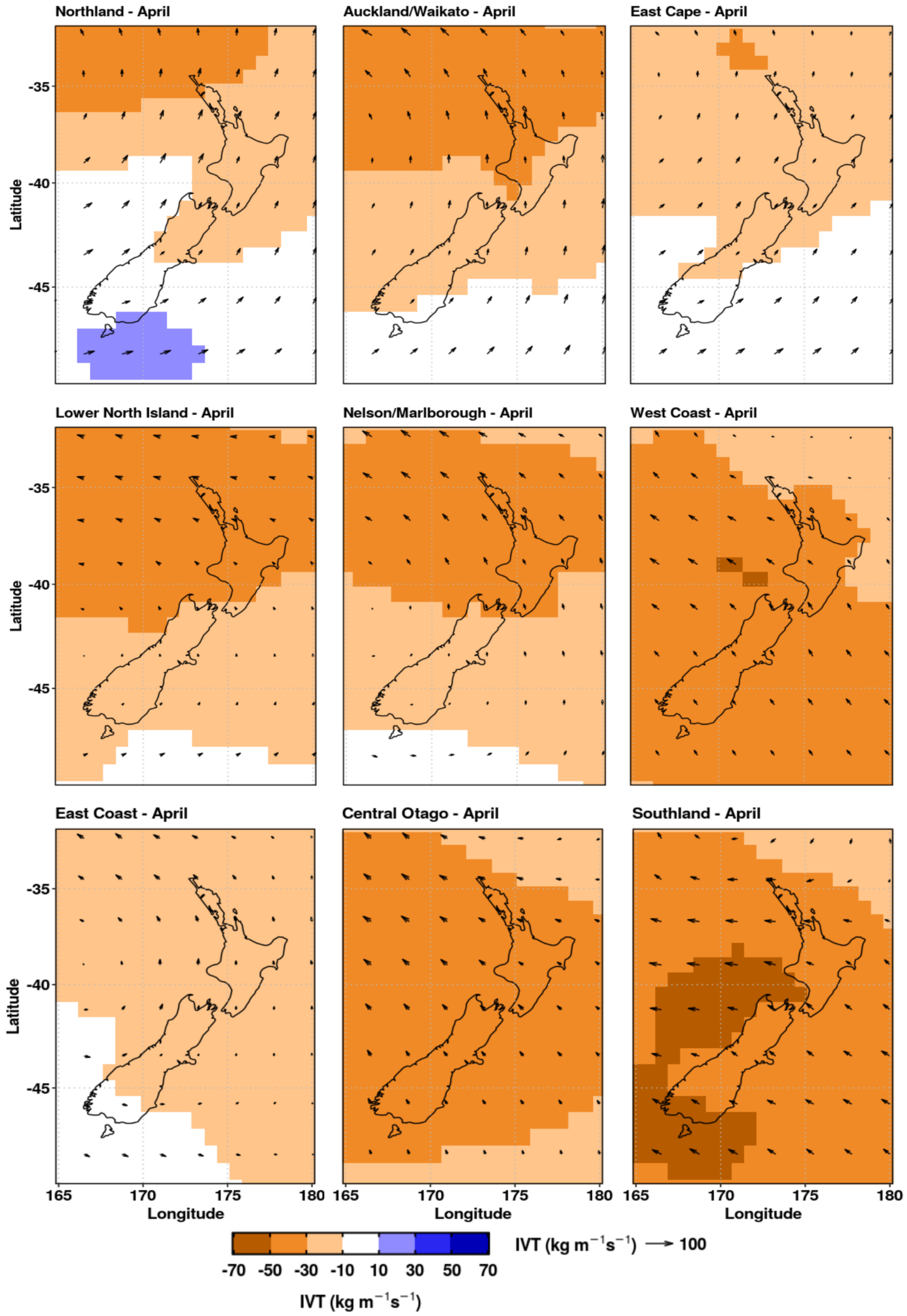
IVT anomalous conditions for February drought events across all regions

March



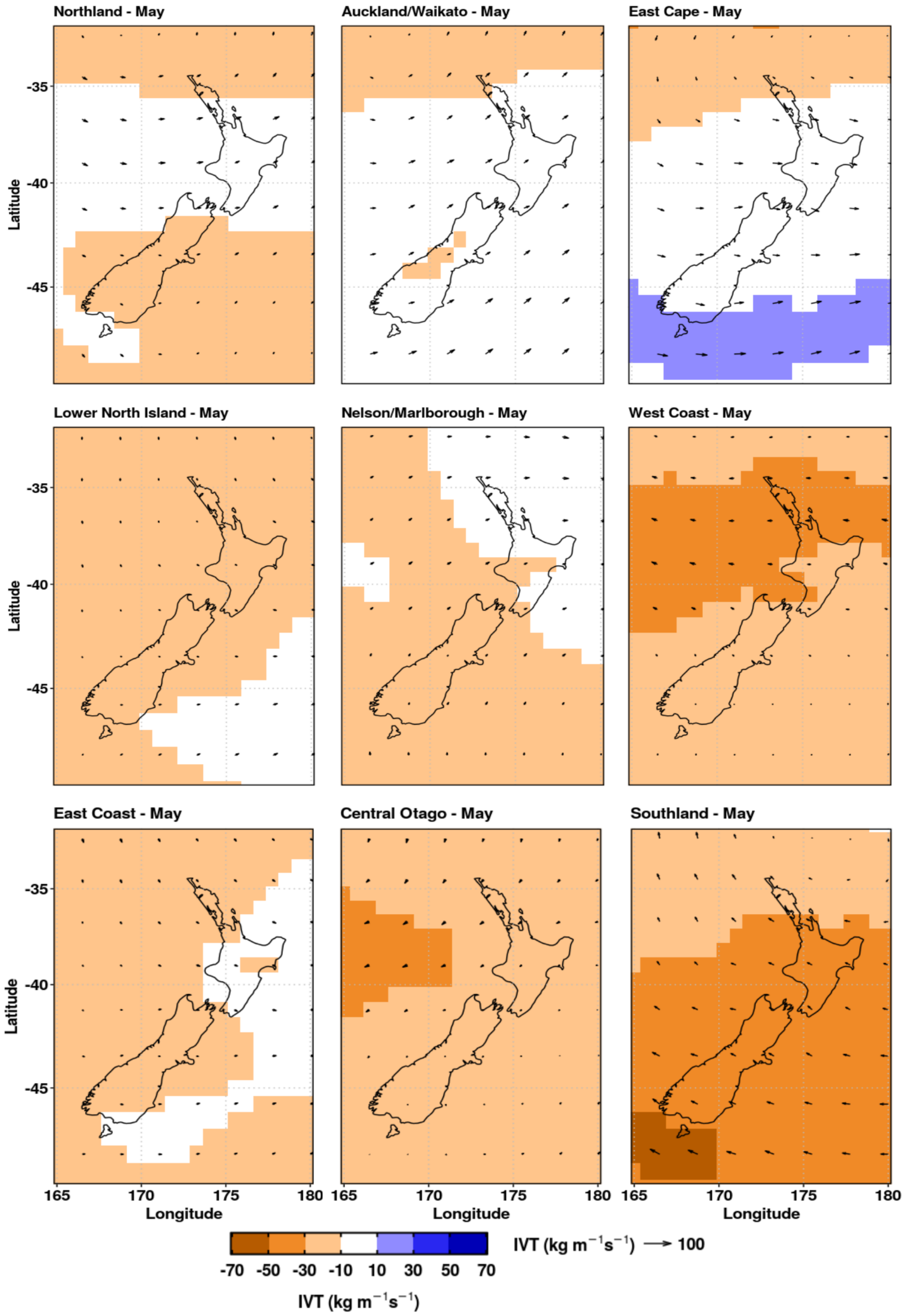
IVT anomalous conditions for March drought events across all regions

April



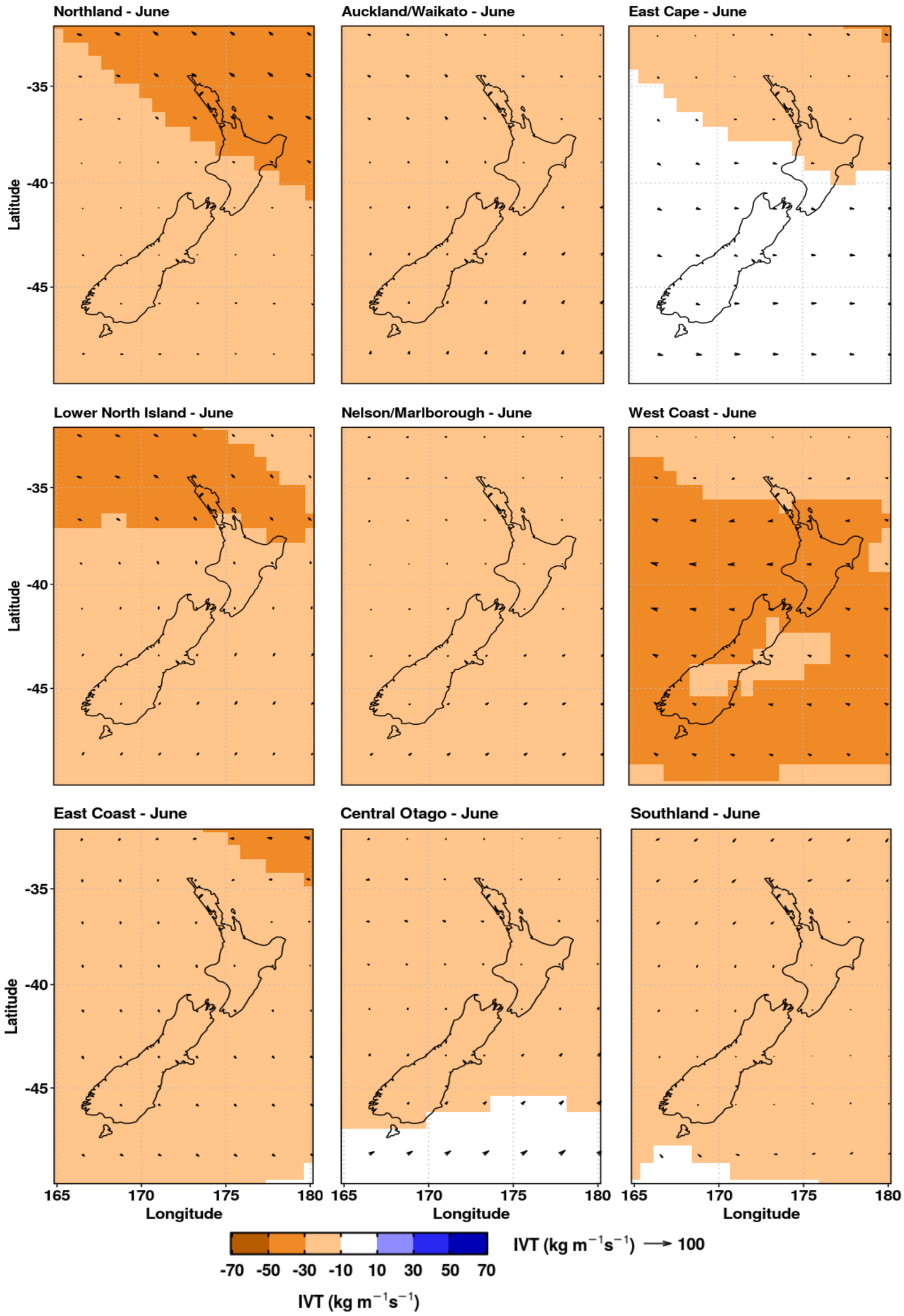
IVT anomalous conditions for April drought events across all regions

May



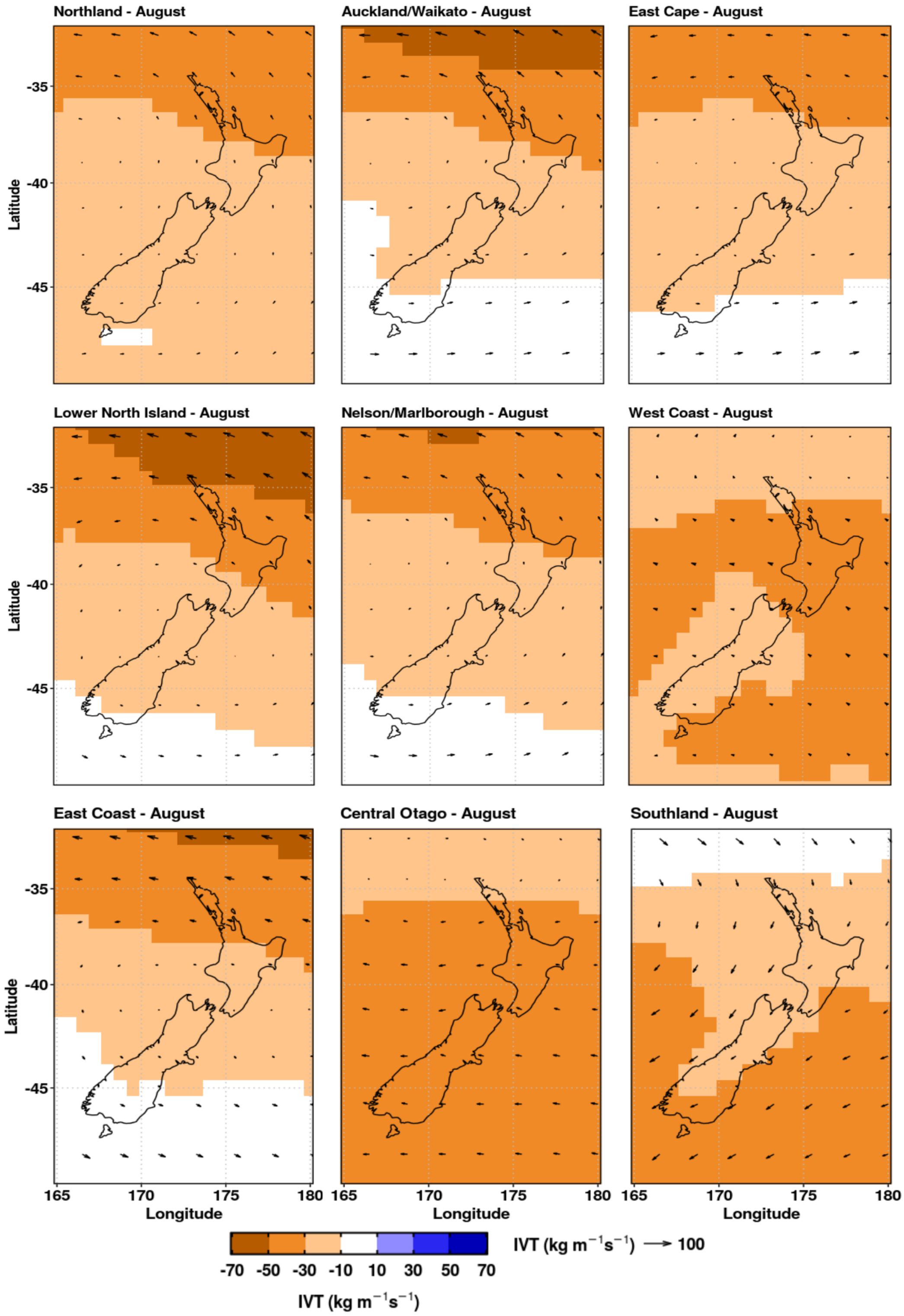
IVT anomalous conditions for May drought events across all regions

June



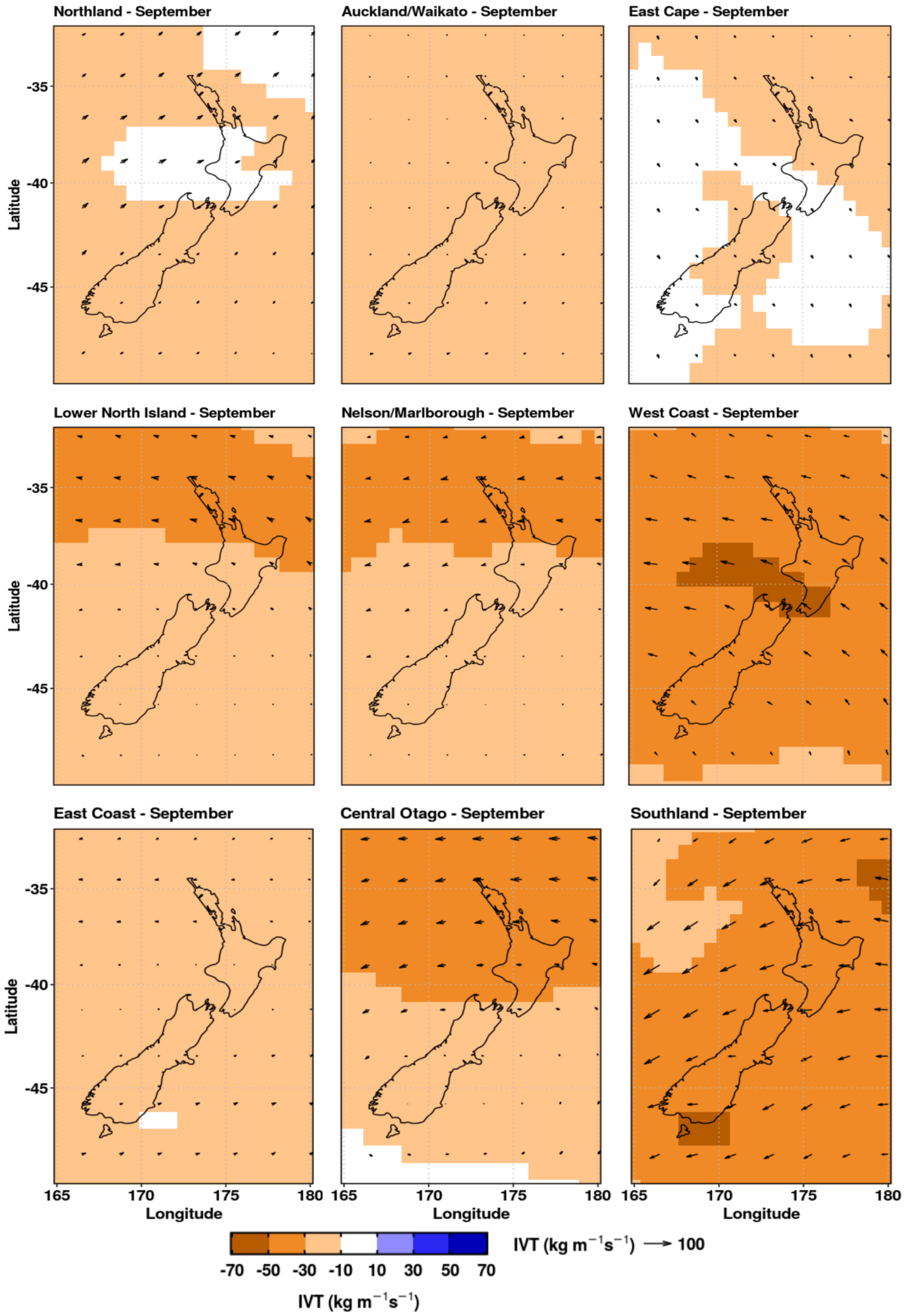
IVT anomalous conditions for June drought events across all regions

August



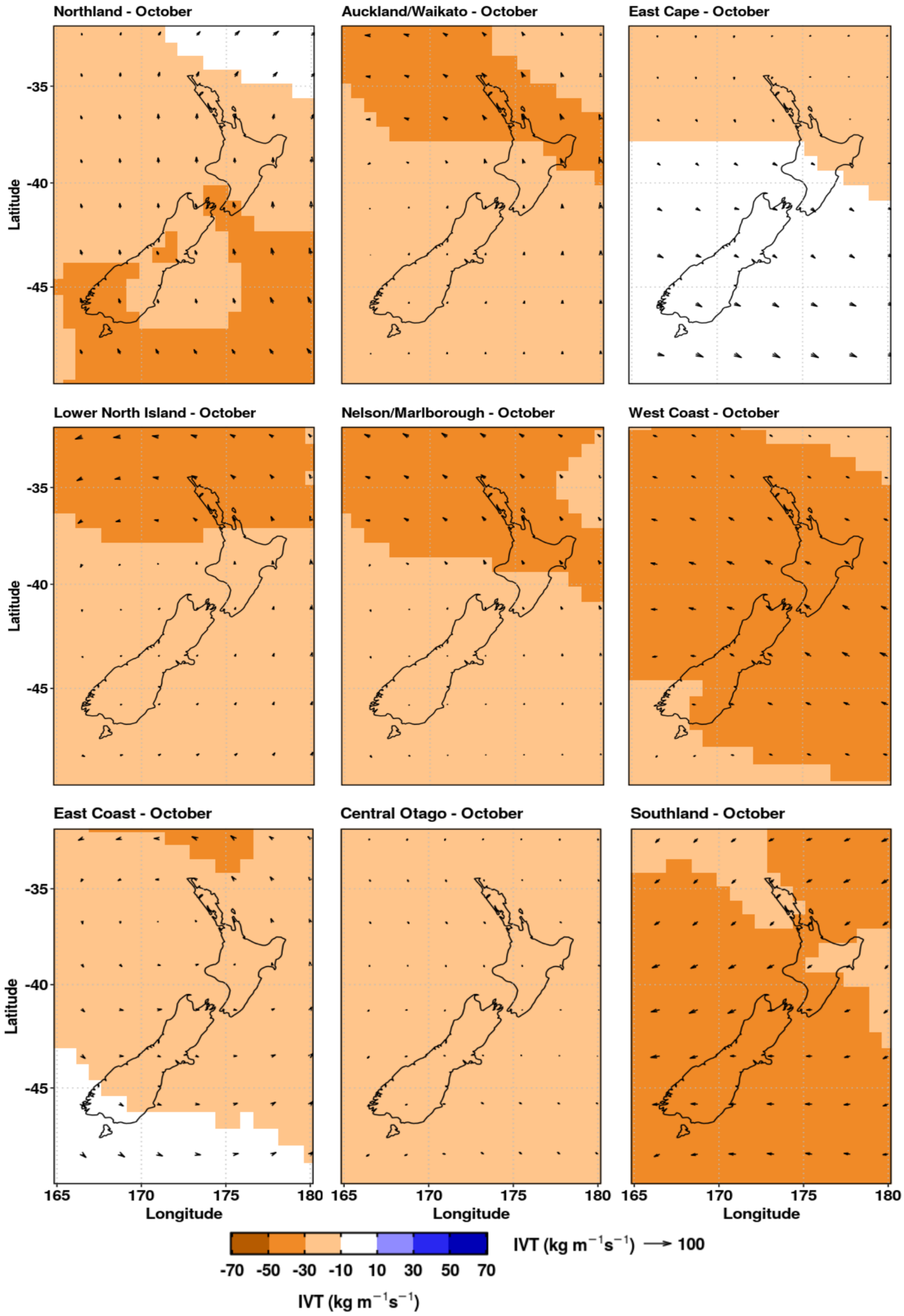
IVT anomalous conditions for August drought events across all regions

September



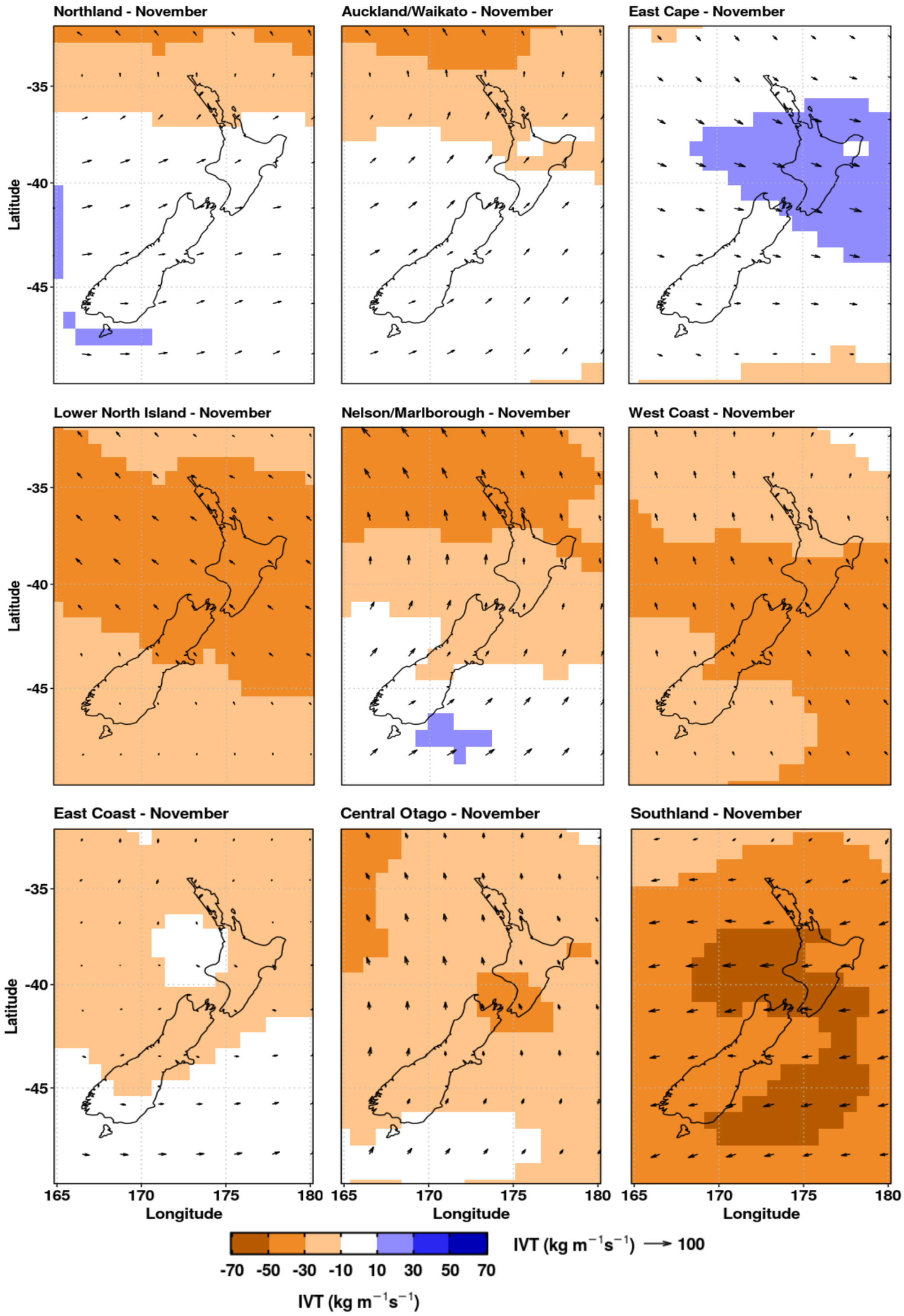
IVT anomalous conditions for September drought events across all regions

October



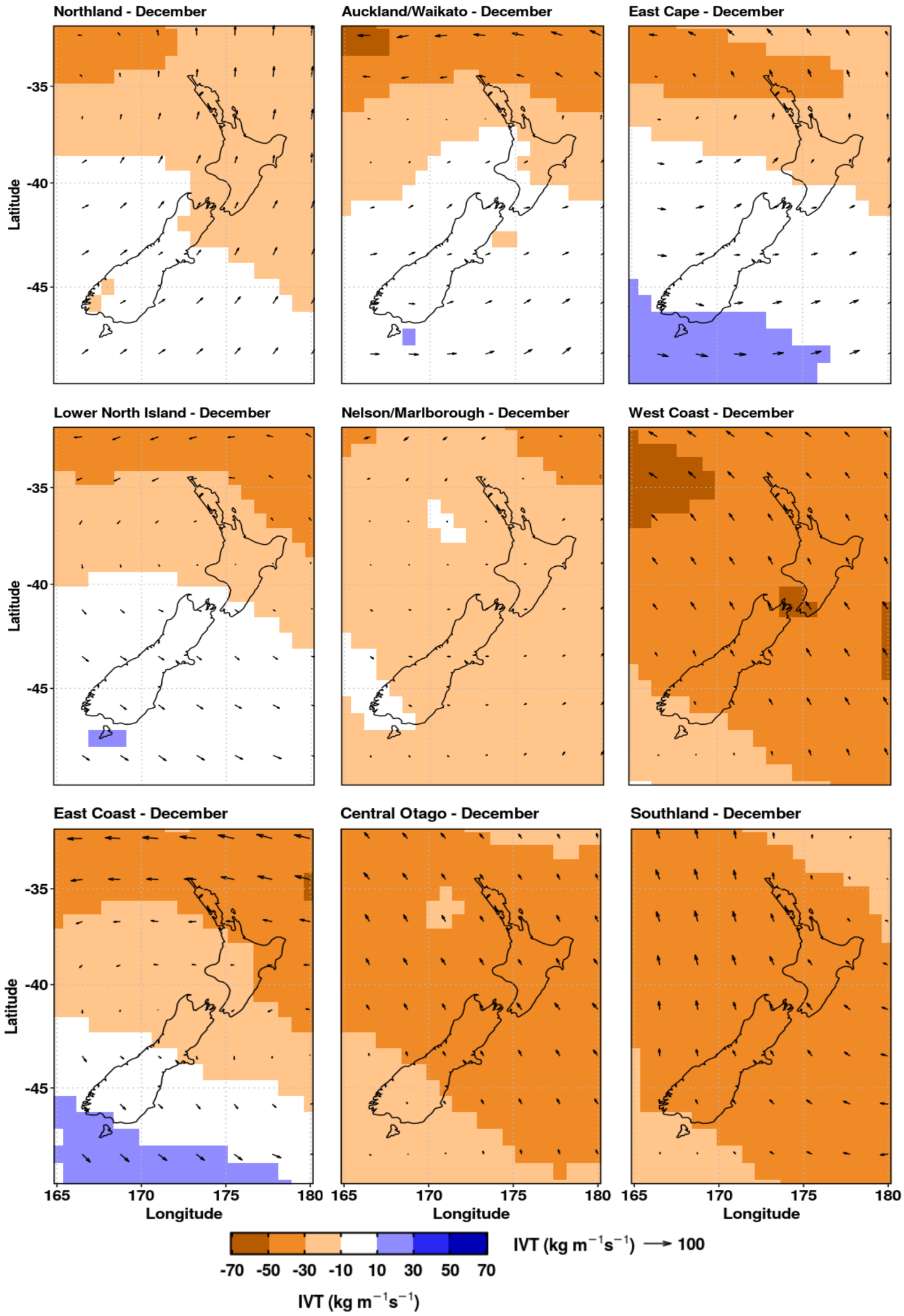
IVT anomalous conditions for October drought events across all regions

November



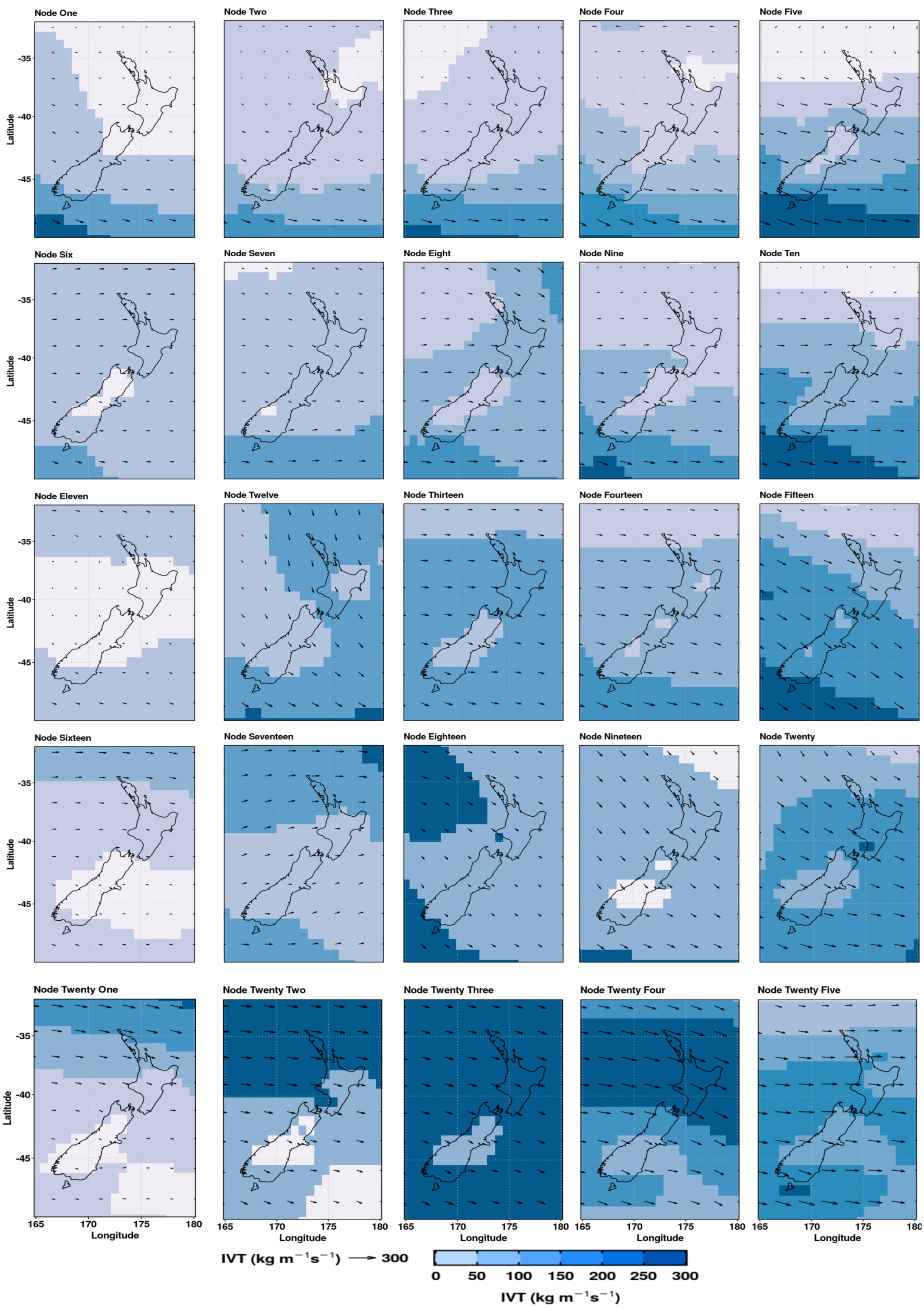
IVT anomalous conditions for November drought events across all regions

December



IVT anomalous conditions for December drought events across all regions

Appendix C: Monthly SOM Nodal Map



IVT patterns during each SOM node, covering the period July 1979 to December 2010

Appendix D: R Package Listing and Reproducible Code

Packages employed in the current thesis include:

library(ncdf4) (Pierce, 2019)

library(raster) (Hijmans, 2020)

library(ggplot2) (Wickham, 2016)

library(ggpubr) (Kassambara, 2020)

library(dplyr) (Wickham *et al.*, 2020)

library(tidyr) (Wickham and Henry, 2020)

library(tidyverse) (Wickham *et al.*, 2019)

library(data.table) (Dowle and Srinivasan, 2019)

library(xtable) (Dahl *et al.*, 2019)

library(zoo) (Zeileis and Grothendieck, 2005)

library(cowplot) (Wilke, 2019)

library(mapproj) (McIlroy *et al.*, 2020)

library(remotes) (Hester *et al.*, 2020)

library(metR) (Campitelli, 2019)

library(RColorBrewer) (Neuwirth, 2014)

library(sp) (Pebesma and Bivand, 2005)

library(forcats) (Wickham, 2020)

library(kohonen) (Wehrens and Kruisselbrink, 2018)

library(ggforce) (Pedersen, 2019)

library(egg) (Auguie, 2019)

Reproducible code is available from https://github.com/MorganBennet/MasterThesis

Appendix E: CDO and Reproducible Code

Australasia Analysis

```
cdo sellonlatbox,90.000,210.000,-70.500,-10.500 ERAInterim
    ↪ ERAInterim_crop
cdo seldate,1979-07-01,2010-12-31 ERAInterim_crop ERAInterim_date
cdo daymean ERAInterim_date ERAInterim_day
cdo monavg ERAInterim_day ERAInterim_month
cdo setvals,-32768,NaN ERAInterim_month ERAInterim_min
cdo setvals,32767,NaN ERAInterim_min ERAInterim_minmax
cdo -selname,p71.162 ERAInterim_minmax ERAInterim_east
cdo -selname,p72.162 ERAInterim_minmax ERAInterim_north
```

New Zealand Analysis

```
cdo sellonlatbox,155.000,190.000,-55.000,-25.000 ERAInterim
    ↪ ERAInterim_crop
cdo seldate,1979-07-01,2010-12-31 ERAInterim_crop ERAInterim_date
cdo daymean ERAInterim_date ERAInterim_day
cdo monavg ERAInterim_day ERAInterim_month
cdo setvals,-32768,NaN ERAInterim_month ERAInterim_min
cdo setvals,32767,NaN ERAInterim_min ERAInterim_minmax
cdo -selname,p71.162 ERAInterim_minmax ERAInterim_east_NZ
cdo -selname,p72.162 ERAInterim_minmax ERAInterim_north_NZ
```